# RECENT EVOLUTIONS AND PERSPECTIVES IN OLYMPIC WINTER SPORTS PERFORMANCE: TO PYEONGCHANG AND BEYOND...

EDITED BY: Gianluca Vernillo, Nicolas Coulmy and Gregoire P. Millet
PUBLISHED IN: Frontiers in Physiology


frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88945-923-0
DOI 10.3389/978-2-88945-923-0

## About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

## Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

## Dedication to Quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view.
By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

## What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: researchtopics@frontiersin.org

# RECENT EVOLUTIONS AND PERSPECTIVES IN OLYMPIC WINTER SPORTS PERFORMANCE: TO PYEONGCHANG AND BEYOND...

Topic Editors:
**Gianluca Vernillo,** University of Milan, Italy
**Nicolas Coulmy,** French Ski Federation, France
**Gregoire P. Millet,** University of Lausanne, Switzerland


Image: Agence Zoom

An evidence-based scientific understanding of factors determining Olympic winter sports performance, recent changes, the evolution in training content and methods, the improvement in technology as well as the occurrence of injury and illness is required. On one hand, this would provide the opportunity to translate research to practice. On the other hand, to guide the practice of Olympic winter sports with the ultimate goal of improving the performance. Certainly, the continued evolution of Olympic winter sports has contributed to an enormous accumulation of knowledge, evidence, and relevant training technologies. Sports sciences, including physiology, conditioning, nutrition, biomechanics, coaching, psychology, as well as sport technology, history and social sciences, have much to contribute to the preparation of the athletes in the Olympic winter sports.

Consequently, this Research Topic sought to provide a platform of contributions to set out a comprehensive framework of the components that should be addressed when developing training plans leading to elite Olympic winter sports performance. Overall, the papers were all directed toward a better understanding of physiological, biomechanical, and training factors related to different Olympic winter sports disciplines: cross-country skiing, alpine skiing, biathlon, Nordic combined, speed skating, snowboarding, and ski-cross.

**Citation:** Vernillo, G., Coulmy, N., Millet, G. P., eds. (2019). Recent Evolutions and Perspectives in Olympic Winter Sports Performance: to PyeongChang and Beyond... Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-923-0

# Table of Contents

frontiers in Physiology

EDITORIAL
published: 24 April 2019
doi: 10.3389/fphys.2019.00481

# Editorial: Recent Evolutions and Perspectives in Olympic Winter Sports Performance: To PyeongChang and Beyond...

*Gianluca Vernillo*[1]*, *Nicolas Coulmy*[2] *and Grégoire P. Millet*[3]

[1] *Department of Biomedical Sciences for Health, University of Milan, Milan, Italy,* [2] *French Ski Federation, Annecy, France,* [3] *Faculty of Biology and Medicine, Institute of Sport Sciences, University of Lausanne, Lausanne, Switzerland*

**Keywords: athlete, olympic games, performance, training, winter sports**

**Editorial on the Research Topic**

**Recent Evolutions and Perspectives in Olympic Winter Sports Performance: To PyeongChang and Beyond. . .**

OPEN ACCESS

***Edited and reviewed by:***
*Gary Iwamoto,*
*University of Illinois*
*at Urbana-Champaign, United States*

***Correspondence:***
*Gianluca Vernillo*
*gianluca.vernillo@gmail.com*

***Specialty section:***
*This article was submitted to*
*Exercise Physiology,*
*a section of the journal*
*Frontiers in Physiology*

***Received:*** *07 March 2019*
***Accepted:*** *05 April 2019*
***Published:*** *24 April 2019*

***Citation:***
*Vernillo G, Coulmy N and Millet GP (2019) Editorial: Recent Evolutions and Perspectives in Olympic Winter Sports Performance: To PyeongChang and Beyond.... Front. Physiol. 10:481. doi: 10.3389/fphys.2019.00481*

## INTRODUCTION

The XXIII Olympic Winter Games were hosted in PyeongChang (South Korea) from the 9th to the 25th of February 2018. The edition included 102 events over 15 disciplines in seven sports. A total of 2,914 athletes from 92 countries competed, including several emerging countries in the winter sports panorama such as Kosovo, Eritrea, Nigeria, and Singapore.

An important goal for most athlete-centered research is to be translated into practice, it is used to inform the development of improved athlete preparation and/or performance (Coutts, 2017). The result of this process is commonly defined as evidence-based practice. Though the efficacy of translating athlete-centered research to practice is still debated (for reasons beyond the scope of this editorial; Bishop, 2008; Coutts, 2017), this Research Topic sought to provide a platform for papers on Olympic winter sports, and set out a comprehensive framework of the different attributes that should be addressed within Olympic winter sports performances. The aim was therefore, on one hand: to better understand factors determining athlete performance, recent changes, the evolution in training content and methods, the improvement in technology, as well as the occurrence of injury and illness across the different Olympic winter sports. On the other hand, we wanted to provide the opportunity not only to translate research to practice, but more importantly to guide the practice of Olympic winter sports, with the ultimate goal of enhancing the performance, improving technological means and equipment, and/or reducing injury risks. Therefore, we focused on issues related to how winter sports athletes meet the acute physiological and biomechanical demands of their winter discipline, and also on the factors that govern some of the long-terms adaptations to exercise training. To explore this, we welcomed the submission of original research, review, perspective articles, and case studies on elite Olympic winter sport athletes, which specifically considered the scope, and impact of their findings in the broader context of Olympic winter sports performance.

## TOPIC CONTENT

A total of 18 papers have been accepted (10 original research papers, four perspectives, two case reports, one review, and a brief research report), written by in total 69 contributing authors from 40 different laboratories (including three winter sports federations) and from 11 countries. Overall, the papers were all directed toward a better understanding of physiological, biomechanical, and training factors related to different Olympic winter sports disciplines: cross-country skiing, alpine skiing, biathlon, Nordic combined, speed skating, snowboarding, and ski-cross.

## CROSS-COUNTRY SKIING

Cross-country skiing is one of the most physiologically demanding sport among the endurance disciplines (Holmberg, 2015). Indeed, it poses significant physiological challenges by means of a combined upper- and lower-body effort. Arm and leg muscles exhibit differences in the way that arm muscles present a lower fat oxidation together with being less oxidative and less capable of extracting $O_2$ (Calbet et al., 2005). Ørtenblad et al. compared the equally trained limb muscles of elite cross-country skiers. They observed that despite the mitochondrial volume percentage and the number of capillaries per fiber area resulted similar in the arms and legs, arms presented more MHC-2 fibers, and larger type 2A fibers (likely due to the demands of the modern cross-country skiing toward rapid generation of large forces during short contact periods). Conversely, lipid metabolism was higher in the leg muscle. These findings can open new perspectives in terms of training regimes applied to the modern cross-country skiing training. However, besides being one of the most physiologically demanding sports, cross-country skiing also involves highly complex biomechanics (Smith, 1990). Pellegrini et al. in their perspective article argued that, throughout modern sport history, cross-country skiing is probably the sport that has evolved the most from a biomechanical and technical point of view. Interestingly, the authors reasoned that despite the enormous changes in recent decades, there still is room for further developments. These improvements include the use of inertial sensors to monitor a skier's speed, motion, and technique continuously and non-invasively. On that matter, Gløersen et al. developed a procedure for estimating the propulsive power generated during roller-skiing using small non-intrusive sensors. The authors observed that the error in the estimation of the propulsive power increased with skiing speed. On the other hand, the propulsive power generated decreased approximately linearly as speed increased. An accurate measurement/estimation of the propulsive power throughout different cross-country ski races is therefore required to improve the understanding of the specific work requirements during cross-country skiing races of different distance. This aspect seems to be of paramount important in cross-country skiing, since Marsland et al. observed differences in the macro-kinematic characteristics utilized during either sprint or distance events. Further, Zoppirolli et al. observed attenuated generation of double-poling forces during a fatiguing 58-km cross-country skiing marathon that could be overcome by maintaining optimal elbow and ankle kinematics and an effective forward lean during the propulsive phase. However, the characterization of cross-country skiing was not merely met in this Research Topic by means of physiological and biomechanical reports. Indeed, from a training perspective, Schmitt et al. highlighted that in elite cross-country skiing athletes the training intensity distribution was shifted toward ∼82% of low intensity training (defined as intensities below the first ventilatory threshold). An important insight has also been provided by Solli and Sandbakk's case study, which described the training characteristics during pregnancy and postpartum in the world's most successful cross-country skier. Notably, the topic of women competing at the elite level while pregnant is an unquestionable important area of research and there is a paucity of controlled physiological studies (Wagner, 2012).

## ALPINE SKIING

The nature of the alpine skiing training toward performance is multifactorial and based on an interaction between intrinsic (e.g., physiological and psychological) and extrinsic (e.g., environment and materials) characteristics (Impellizzeri et al., 2009). An interesting perspective article covering this aspect has been done by Gilgien et al. The authors, by means of a survey administered to the coaching staff, described how Olympic athletes from Germany, Norway, Sweden, and Switzerland prepared the XXIII Olympic Winter Games in PyeongChang (South Korea) in 2018. The survey items were based on the athletes' typical exercise programs with respect to physical conditioning, ski training, and periodization. Notably, the authors highlighted how the training periodization does not typically follow a traditional annual cycle; rather it is influenced by the availability of good in-snow training conditions. Two distinct characteristics of the alpine skiing training were also highlighted: the importance of strength training (in its different forms) and the careful attention given to training in hypoxic environments. The interaction between hypoxia and strength has been the object of Alhammoud et al.'s study, who explored the effects of acute hypoxia on maximal (as well as explosive) torque and fatigability in the knee extensors of elite alpine skiers. This highlighted the importance of considering explosive strength measurements in the alpine skiing neuromuscular screening tests and prevention programs. The training management between in- and off-snow period is a challenging aspect of alpine skiing (Turnbull et al., 2009). In order to address this issue, Stöggl et al. explored the feasibility of using a dryland ski ergometer as a training tool. Results showed that the high intensity training protocols administered with the ski ergometer were able to achieve a high level of cardiorespiratory and metabolic responses. This highlights the feasibility of using a ski ergometer during the off-snow period in alpine skiing to effectively train the endurance component. However, alpine skiing is a complex winter sport discipline and requires not only high levels of physical capacities (Andersen and Montgomery, 1988; Raschner et al., 2017) but also complex biomechanical features. This aspect has been the object of three papers accepted in this Research Topic. Supej and Holmberg provided an update on the biomechanics of alpine skiing, highlighting the importance of the inclusion of measurement technologies in order to optimize the coaches' work. Some of these technologies have been explored by Fasel et al. and Meyer and Borrani. Fasel et al. presented and validated a method to correct velocity and position drift for inertial sensor-based measurements. Whereas, Meyer and Borrani explored the link between the antenna trajectory of global navigation satellite system and the alpine skiers' center of mass.

## BIATHLON

Biathlon combines rifle marksmanship and cross-country skiing while carrying a rifle. It presents similar physiological requirements to those observed for cross-country skiing (Holmberg, 2015) together with precise fine motor control for fast and accurate shooting (Vickers and Williams, 2007). The extensive perspective article by Laaksonen et al. covered both training and technical (i.e., skiing and shooting) aspects of modern biathlon, highlighting the needs to concurrently optimize physiological and performance capacities of cross-country skiing techniques with shooting.

## NORDIC COMBINED

As described by Rasdal et al. (2017), Nordic combined is an Olympic winter sport where the athletes have to compete in both a ski-jumping event and a cross-country skiing race on the same day. Despite existing similarities, cross-country skiers, and Nordic combined athletes possess different characteristics and training contents (Sandbakk et al., 2016). This was also interestingly observed by Schmitt et al. who presented differences in the training intensity distribution between cross-country skiers and Nordic combined athletes. If cross-country skiers presented a training intensity distribution shifted toward low intensity training regimes (see above), Nordic combined athletes presented a lower low intensity volume (∼51%) but higher strength and speed training (∼39%). In support of this, Rasdal et al. presented the case study of a Nordic combined champion, highlighting his training, and technical and physiological development during the last four seasons preceding the XXIII Olympic Winter Games in PyeongChang (South Korea) in 2018.

## SPEED SKATING

Speed skating is a peculiar sport in which athletes adopt a crouched position and push-off sideward in order to move forward (Noordhof et al., 2014). The characteristics of speed skating contribute to impede blood flow and exacerbate deoxygenation in the lower limbs that is remarkably greater for short- vs. long-track speed skating (Hettinga et al., 2016). Richard and Billaut explored whether or not combining preconditioning strategies could modify muscular oxygenation and improve speed skating performance. Results showed that a preconditioning strategy of combined remote ischemic preconditioning and inspiratory muscle warm-up did not significantly impact the 600-m speed skating performance in elite skaters. This highlights the need for further studies to clearly identify positive strategies to impact speed skating performance, particularly by reducing skeletal muscle deoxygenation.

## SNOWBOARDING

Similar to alpine skiing, snowboarding requires high technical skills, leg strength, dynamic ability as well as aerobic and anaerobic capacity (Vernillo et al., 2016a,b, 2017). Though snowboarding has grown in popularity as an Olympic winter sport, only a small number of studies analyzing the physiological and performance characteristics, as well as the requirements of snowboarding, have been published thus far. The review by Vernillo et al. explores the current literature providing insights into the physiological and physical characteristics of snowboarding performance. It revealed the need to improve our current understanding of snowboarding, as well as its physiological and performance profiles, in order to more effectively train snowboarding athletes.

## SKI-CROSS

Ski-cross is a type of skiing competition where four skiers are required to maneuver inside a course characterized by multiple obstacles (e.g., banks and jumps). A distinctive feature of this discipline is that athletes can take advantage of the so-called slipstreaming (or drafting) to catch up with the leading athlete. If slipstreaming is a well-studied strategy in those sports where the preservation of muscle power is a fundamental requirement (e.g., cycling, speed skating, and running), then how it affects gravity-powered sports is less investigated. Fuss derived a strategy for slipstreaming in ski-cross by means of a glide model. Results showed that the glide model could be used to test the design of the slope track, precisely identifying the dimensions of the terrain features, and thereby deriving the skiers' speed as well as identifying the critical section of the course.

## CONCLUSION

The scientific basis of Olympic winter sports, as well as the studies of how athletes cope with the specific physiological and biomechanical requirements of their discipline, is of paramount importance and interest for exercise physiologists, sport scientists, and particularly coaches. These studies are necessary in order to improve the current understanding of Olympic winter sports performance. The continued evolution of Olympic winter sports is contributing to an enormous accumulation of knowledge, evidence, and relevant training technologies. In this context, the 18 papers that constitute this Research Topic have contributed to our better understanding of the requirements of different Olympic winter sports. The field of study is enormous and touches a considerable number and range of issues. We hope this Research Topic will contribute to the stimulation of further research in all the aspects highlighted within it. The ultimate goal being to improve all Olympic winter sports performances. With the recent implementation by the International Olympic Committee of the Youth Olympic Games, further research is also required to better analyse the practice of winter sports by young athletes at the elite level. Questions about the optimal increase in training load and the specificity of the training content at different age-stages for reducing health and risk of injury are paramount and yet minimally investigated. The next step might come from the "Youth and Winter Sports" congress being held from the 7th to the 8th of January 2020 in Lausanne (Switzerland) prior the next winter Youth Olympic Games, also hosted in Lausanne from the 9th to the 22nd of January 2020.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

## REFERENCES


Andersen, R. E., and Montgomery, D. L. (1988). Physiology of alpine skiing. *Sports Med*. 6, 210–221. doi: 10.2165/00007256-198806040-00003

Bishop, D. (2008). An applied research model for the sport sciences. *Sports Med*. 38, 253–263. doi: 10.2165/00007256-200838030-00005

Calbet, J. A., Holmberg, H. C., Rosdahl, H., van Hall, G., Jensen-Urstad, M., and Saltin, B. (2005). Why do arms extract less oxygen than legs during exercise? *Am. J. Physiol. Regul. Integr. Comp. Physiol*. 289, R1448–R1458. doi: 10.1152/ajpregu.00824.2004

Coutts, A. J. (2017). Challenges in developing evidence-based practice in high-performance sport. *Int. J. Sports Physiol. Perform*. 12, 717–718. doi: 10.1123/IJSPP.2017-0455

Hettinga, F. J., Konings, M. J., and Cooper, C. E. (2016). Differences in muscle oxygenation, perceived fatigue and recovery between long-track and short-track speed skating. *Front. Physiol*. 7:619. doi: 10.3389/fphys.2016.00619

Holmberg, H. C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scand. J. Med. Sci. Sports*. 25 (Suppl. 4), 100–109. doi: 10.1111/sms.12601

Impellizzeri, F. M., Rampinini, E., Freschi, M., Maffiuletti, N. A., Bizzini, M., and Mognoni, P. (2009). "Identification of the physical characteristics that discriminate between competitive levels and specialities of alpine skiers," in *Science and Skiing IV,* eds E. Muller, S. Lindinger, and T. Stöggl (Aachen: Meyer & Meyer Sport), 272–280.

Noordhof, D. A., Foster, C., Hoozemans, M. J., and de Koning, J. J. (2014). The association between changes in speed skating technique and changes in skating velocity. *Int. J. Sports Physiol. Perform*. 9, 68–76. doi: 10.1123/ijspp.2012-0131

Raschner, C., Hildebrandt, C., Mohr, J., and Muller, L. (2017). Sex differences in balance among alpine ski racers: cross-sectional age comparisons. *Percept. Mot. Skills*. 124, 1134–1150. doi: 10.1177/0031512517730730

Rasdal, V., Fudel, R., Kocbach, J., Moen, F., Ettema, G., and Sandbakk, O. (2017). Association between laboratory capacities and world-cup performance in Nordic combined. *PLoS ONE* 12:e0180388. doi: 10.1371/journal.pone.0180388

Sandbakk, O., Rasdal, V., Braten, S., Moen, F., and Ettema, G. (2016). How do world-class nordic combined athletes differ from specialized cross-country skiers and ski jumpers in sport-specific capacity and training characteristics? *Int. J. Sports Physiol. Perform*. 11, 899–906. doi: 10.1123/ijspp.2015-0285

Smith, G. A. (1990). Biomechanics of crosscountry skiing. *Sports Med*. 9, 273–285. doi: 10.2165/00007256-199009050-00003

Turnbull, J. R., Kilding, A. E., and Keogh, J. W. (2009). Physiology of alpine skiing. *Scand. J. Med. Sci. Sports* 19, 146–155. doi: 10.1111/j.1600-0838.2009.00901.x

Vernillo, G., Pisoni, C., Sconfienza, L. M., Thiebat, G., and Longo, S. (2017). Changes in muscle architecture of vastus lateralis muscle after an alpine snowboarding race. *J. Strength Cond. Res*. 31, 254–259. doi: 10.1519/JSC.0000000000001469

Vernillo, G., Pisoni, C., and Thiebat, G. (2016a). Physiological characteristics of elite snowboarders. *J. Sports Med. Phys. Fitness* 56, 527–533.

Vernillo, G., Pisoni, C., and Thiebat, G. (2016b). Strength asymmetry between front and rear leg in elite snowboard athletes. *Clin. J. Sport Med*. 26, 83–85. doi: 10.1097/JSM.0000000000000194

Vickers, J. N., and Williams, A. M. (2007). Performing under pressure: the effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *J Mot. Behav*. 39, 381–394. doi: 10.3200/JMBR.39.5.381-394

Wagner, P. D. (2012). On completing a marathon and giving birth the same day. *J. Appl. Physiol.* 113:987. doi: 10.1152/japplphysiol.00659.2012


**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 02 August 2018
doi: 10.3389/fphys.2018.01031

Check for updates

# The Muscle Fiber Profiles, Mitochondrial Content, and Enzyme Activities of the Exceptionally Well-Trained Arm and Leg Muscles of Elite Cross-Country Skiers

*Niels Ørtenblad[1,2]*, Joachim Nielsen[1], Robert Boushel[2], Karin Söderlund[3], Bengt Saltin[4†] and Hans-Christer Holmberg[5,6]*

[1] Department of Sports Science and Clinical Biomechanics, SDU Muscle Research Cluster, University of Southern Denmark, Odense, Denmark, [2] School of Kinesiology, University of British Columbia, Vancouver, BC, Canada, [3] Åstrand Laboratory, The Swedish School of Sport and Health Sciences, Stockholm, Sweden, [4] Copenhagen Muscle Research Centre, Copenhagen, Denmark, [5] Swedish Winter Sports Research Centre, Mid Sweden University, Östersund, Sweden, [6] School of Sport Sciences, UiT The Arctic University of Norway, Tromsø, Norway

OPEN ACCESS

**Edited by:**
Gregoire P. Millet,
Université de Lausanne, Switzerland

**Reviewed by:**
Stefanos Volianitis,
Aalborg University, Denmark
Louise Deldicque,
Université catholique de Louvain,
Belgium

***Correspondence:**
Niels Ørtenblad
nortenblad@health.sdu.dk

† Deceased

**Specialty section:**
This article was submitted to
Exercise Physiology,
a section of the journal
Frontiers in Physiology

**Received:** 09 May 2018
**Accepted:** 11 July 2018
**Published:** 02 August 2018

**Citation:**
Ørtenblad N, Nielsen J, Boushel R, Söderlund K, Saltin B and Holmberg H-C (2018) The Muscle Fiber Profiles, Mitochondrial Content, and Enzyme Activities of the Exceptionally Well-Trained Arm and Leg Muscles of Elite Cross-Country Skiers. Front. Physiol. 9:1031. doi: 10.3389/fphys.2018.01031

As one of the most physically demanding sports in the Olympic Games, cross-country skiing poses considerable challenges with respect to both force generation and endurance during the combined upper- and lower-body effort of varying intensity and duration. The isoforms of myosin in skeletal muscle have long been considered not only to define the contractile properties, but also to determine metabolic capacities. The current investigation was designed to explore the relationship between these isoforms and metabolic profiles in the arms (*triceps brachii*) and legs (*vastus lateralis*) as well as the range of training responses in the muscle fibers of elite cross-country skiers with equally and exceptionally well-trained upper and lower bodies. The proportion of myosin heavy chain (MHC)-1 was higher in the leg (58 ± 2% [34–69%]) than arm (40 ± 3% [24–57%]), although the mitochondrial volume percentages [8.6 ± 1.6 (leg) and 9.0 ± 2.0 (arm)], and average number of capillaries per fiber [5.8 ± 0.8 (leg) and 6.3 ± 0.3 (arm)] were the same. In these comparable highly trained leg and arm muscles, the maximal citrate synthase (CS) activity was the same. Still, 3-hydroxy-acyl-CoA-dehydrogenase (HAD) capacity was 52% higher ($P < 0.05$) in the leg compared to arm muscles, suggesting a relatively higher capacity for lipid oxidation in leg muscle, which cannot be explained by the different fiber type distributions. For both limbs combined, HAD activity was correlated with the content of MHC-1 ($r^2 = 0.32$, $P = 0.011$), whereas CS activity was not. Thus, in these highly trained cross-country skiers capillarization of and mitochondrial volume in type 2 fiber can be at least as high as in type 1 fibers, indicating a divergence between fiber type pattern and aerobic metabolic capacity. The considerable variability in oxidative metabolism with similar MHC profiles provides a new perspective on exercise training. Furthermore, the clear differences between equally well-trained arm and leg muscles regarding HAD activity cannot be explained by training status or MHC distribution, thereby indicating an intrinsic metabolic difference between the upper and lower body. Moreover, trained type 1 and type 2A muscle fibers exhibited similar aerobic capacity regardless of whether they were located in an arm or leg muscle.

**Keywords: limb muscles, fiber plasticity, training, capillarization, mitochondria, IMCL, cross-country skiing**

## INTRODUCTION

Among the most demanding of Olympic sports, cross-country skiing competitions on varying terrain require the use of a variety of skiing techniques that involve the upper and/or lower body to different extents. In recent decades, this primarily endurance sport has changed to include novel events such as pursuit, mass-start, and sprint races, with head-to-head competitions and a wider range of speeds. Improved track preparation, equipment, and skiing techniques, in combination with more effective training (especially of upper-body strength/power and endurance), have elevated racing speeds in general (Holmberg, 2015).

The necessity for today's elite cross-country skier to combine considerable endurance with rapid generation of high forces during short contacts with the ground has enhanced focus on optimizing related morphological and metabolic adaptations in the skeletal muscles of the upper and lower body (Holmberg et al., 2005). The relatively unique situation that both the leg and arm muscles of elite cross-country skiers are highly trained has allowed important comparisons that have helped provide novel insights into the limits of physiological regulation and performance, thereby helping to improve training routines.

Skeletal muscles are composed of motor units, containing muscle fibers with the same specific characteristics (Canepari et al., 2010). In general, muscle fibers are distinguished from one another on the basis of (1) the contractile apparatus [myosin heavy chain (MHC) or ATPase isoforms]; (2) contractile characteristics (fast vs. slow twitch); (3) $Ca^{2+}$ handling properties and metabolic profile (oxidative or glycolytic), with the golden standard being the MHC-isoform (Schiaffino and Reggiani, 2011). The functional significance of the MHC isoform for its contractile characteristics is well established (Schiaffino and Reggiani, 2011), even for hybrid fibers co-expressing MHC isoforms. The metabolic capacity of the muscle fiber is dependent on the degree of capillarization, substrate availability and mitochondrial content, while the $Ca^{2+}$ handling properties are dependent on sarcoplasmic reticulum (SR) content and property (Stephenson et al., 1998; Ørtenblad et al., 2000b; Gejl et al., 2014). The metabolic and $Ca^{2+}$ handling properties are generally considered as being linked with contractile fiber type characteristics. Human muscle fibers expressing MHC-1 have the highest oxidative capacity while having slow shortening velocity (incl. excitation–contraction coupling) and slower $Ca^{2+}$ handling, whereas MHC-2 fibers have the opposite characteristics. However, metabolic variation within each fiber type and fibers in arm and leg muscle is less well explored, both with regard to extent and influence on the metabolic response of the fiber.

Most Olympic disciplines involve mainly the legs and lower body, with fewer combining upper and lower body as in cross-country skiing. Despite the importance of the arms in sports such as swimming, rowing, and cross-country skiing, our knowledge of arm muscle physiology is considerably less than in the case of the legs and warrants more attention. The few direct comparisons of arm and leg muscles indicate that arm muscles are less oxidative and less capable of extracting oxygen from the circulation, irrespective of training status, with greater variability in blood flow during exercise (Van Hall et al., 2003; Calbet et al., 2005). Furthermore, exercising arm muscle has evidently a lower fat oxidation compared to leg muscle (Calbet et al., 2005; Helge, 2010). However, the physiological comparison of arms and legs is hampered by an often-unequal training status of the limbs. Thus, direct comparisons of the highly trained arm and leg muscles of elite cross-country skiers can be made unequivocally.

Accordingly, the current investigation assessed further the metabolic capacity in the upper and lower body of such skiers, as well the potential relationship between the various isoforms of MHCs and metabolic profile. For this purpose, we examined type 1 and type 2 fibers from leg (*vastus lateralis*) muscle and arm muscle (*triceps brachii*) from successful cross-country skiers with exceptionally well-trained lower and upper body. Our hypotheses were that (1) there are intrinsic metabolic differences between equally well-trained arm and leg muscles and (2) type1 and type 2 muscle fibers possess similarly metabolic capacity, regardless of their location in an arm or leg muscle and that this possible adaptation is not linked to the isoform of the muscle fibers.

## MATERIALS AND METHODS

### Subjects

Ten elite male Norwegian cross-country skiers participated in the study, as part of a larger project and related data from the project has already been published (Nielsen et al., 2011; Ørtenblad et al., 2011; Koh et al., 2017). Their mean (±SD) age, height, weight, and $\dot{V}O_{2max}$ were 22 ± 1 yr, 181 ± 2 cm, 79 ± 8 kg, and 5.37 ± 0.46 $L\cdot min^{-1}$ (69 ± 5 $ml\cdot kg^{-1}\cdot min^{-1}$), respectively (**Table 1**) and a hematocrit of 47 ± 1% and hemoglobin of 155 ± 2 mmol/l. These skiers had trained systematically for an average of 11 years; six had competed as members of the Norwegian national team; and eight competed in the FIS World Cup the year after this study, with one winning a World Cup race (**Table 1**). All subjects were informed of the test procedures and potential risks prior to providing their written informed consent to participate. The research procedures and experimental protocol were pre-approved by the Human Ethics Committee

**TABLE 1 |** Characteristics of the 10 elite male cross-country skiers who participated in this study.

| Subject | Age (years) | Weight (kg) | Height (cm) | $VO_2$ max ($L \cdot min^{-1}$) | $VO_2$ max ($mL \cdot kg^{-1} \cdot min^{-1}$) | Performance |
|---|---|---|---|---|---|---|
| 1 | 22 | 81.4 | 190 | 5.82 | 71.5 | 12th in WC 50-km C (2012) |
| 2 | 21 | 77.2 | 182 | 5.10 | 66.1 | among the top 30/15 in NOR Tr and Sp, respectively |
| 3 | 22 | 87.3 | 188 | 6.08 | 69.6 | among the top 30 in NOR Tr |
| 4 | 19 | 76.0 | 178 | 5.21 | 68.6 | 12th in NNC Sp (2009) |
| 5 | 21 | 77.2 | 178 | 5.16 | 66.8 | 40th in NNC 15F (2011) |
| 6 | 23 | 66.8 | 172 | 5.30 | 79.3 | 9th in WC 15-km F (2008) |
| 7 | 23 | 92.4 | 193 | 6.05 | 65.5 | 14th in WC Sp (2011) |
| 8 | 23 | 87.1 | 179 | 5.34 | 61.3 | Among the top 50 and 30 in NOR Tr and Sp, respectively |
| 9 | 24 | 69.9 | 175 | 4.82 | 69.0 | Among the top 30 in NOR Sp |
| 10 | 22 | 72.5 | 173 | 4.85 | 66.9 | Among the top 60 in NOR |
| Mean ± SD | 22 ± 1 | 78.8 ± 8.2 | 181 ± 7 | 5.37 ± 0.46 | 68.5 ± 4.7 | |

*WC, World Cup; NC, Norwegian National Championship; Tr, traditional/longer distances; Sp, sprint distances; C, classical technique; F, free technique.*

of Umeå University, Sweden (#07-076M), and performed in accordance with the Declaration of Helsinki.

## Procedures

### Laboratory Tests

$\dot{V}O_{2max}$ was determined during diagonal skiing with roller skis on a treadmill (Rodby, Södertälje, Sweden; Calbet et al., 2005), starting at 11 $km \cdot h^{-1}$ on a treadmill inclination of 4° and increasing the incline by 1° each minute until exhaustion. During the tests, each subject was secured with a safety harness suspended from the ceiling. For the subjects, roller skiing on the treadmill was a regular part of their training.

Respiratory variables were determined with the mixed expired gas procedure, employing an ergo-spirometry system (AMIS 2001 model C, Innovision A/S, Glamsbjerg, Denmark) equipped with an inspiratory flowmeter. The gas analyzers were calibrated with a high-precision mixture of 16.0% $O_2$ and 4.0% $CO_2$ (Air Liquide, Kungsängen, Sweden) and the flowmeter calibrated at low, medium, and high flow rates with a 3-l air syringe (Hans Rudolph, Kansas City, MO, United States). Ambient conditions were monitored with an external apparatus (Vaisala PTU 200, Vaisala OY, Helsinki, Finland). Expired $O_2$ and $CO_2$ and the inspired minute ventilation ($V\dot{E}$) were monitored continuously and $VO_2$ values averaged during the final 30 s at each workload. Heart rate was recorded continuously by the Polar S610 monitor (Polar Electro Oy, Kempele, Finland).

### Muscle Biopsy Preparation and Analysis

Muscle biopsies were taken from leg and arm muscles and standardization of the location on the muscle and muscle depth was ensured. After local anesthesia (2–3 ml 2% lidocaine), an incision was made through the skin and fascia and the muscle biopsy was taken from the *vastus lateralis* (leg) and *triceps brachii* (distal part of the lateral head, arm), using a modified Bergström needle with suction. These muscles were selected because they are very active during cross-country skiing (Komi and Norman, 1987; Holmberg et al., 2005). The skiers had four biopsies taken from both arm and leg muscle. The muscle specimen was dried on filter paper and placed on a glass plate cooled on ice. After the removal of visible connective tissue and fat, each muscle specimen was divided into four specimens then handled in the following ways: (1) frozen directly in liquid $N_2$ and stored for later analyses of enzyme activity and glycogen content; (2) fixed for transmission electron microscopy (TEM) analysis; (3) 10–20 mg was mounted in an embedding medium (OCT compound), frozen rapidly in isopentane pre-cooled with liquid $N_2$, and stored at −80°C for later histochemical analysis; or (4) a segment was weighed and homogenized in 10 volumes (wt/vol) of ice-cold buffer (300 mM sucrose, 1 mM EDTA, 10 mM $NaN_3$, 40 mM Tris-base, and 40 mM histidine at pH 7.8) at 0°C in a 1-ml glass homogenizer with a glass pestle (Kontes Glass Industry, Vineland, NJ, United States). Prior to homogenization, the muscle sample was rinsed free of contaminating blood by washing it in an ice-cold buffer. The homogenate was analyzed for protein content and MHC composition. All in all 40 biopsies were obtained from the leg and arm muscles, and in one biopsy from arm, the sample portion was not large enough to obtain CS activity.

### Myosin Heavy Chain Composition

Myosin heavy chain composition was analyzed using gel electrophoresis. Briefly, muscle homogenate (80 μl) was mixed with 200 μl sample buffer (10% glycerol, 5% 2-mercaptoethanol, 2.3% SDS, 62.5 mM Tris-base, and 0.2% bromophenolblue at pH 6.8), boiled in a water bath at 100°C for 3 min, and loaded with three different amounts of protein (10–40 μl) on an SDS-PAGE gel [6% polyacrylamide (100:1, acrylamide:bis-acrylamide), 30% glycerol, 67.5 mM Tris-base, 0.4% SDS, and 0.1 mM glycine]. Gels were run at 80 V for at least 42 h at 4°C and MHC bands made visible by staining with Coomassie and three separate bands could be detected and characterized as MHC-1, MHC-2A, and MHC-2X. The gels were scanned (Linoscan 1400 scanner, Heidelberg, Germany) and the MHC bands were quantified densitometrically (Phoretix 1D, nonlinear, Newcastle, United Kingdom). MHC-2 was identified with Western blot using monoclonal antibody (Sigma M 4276) with the Xcell IITM protocol (Invitrogen, Carlsbad, CA, United States). All values presented are the means of three biopsies (two from one leg/arm and one from the other leg/arm), utilizing three different concentrations of protein from each biopsy.

### Enzyme Activity

The maximal activities of 3-hydroxy-acyl-CoA-dehydrogenase (HAD) and citrate synthase (CS), were determined fluorometrically at 25°C (Lowry and Passonneau, 1972) in freeze-dried muscle dissected free of non-muscle constituents. CS activity was determined by the addition of oxaloacetate to a buffer solution containing muscle homogenate, DTNB buffer, acetyl-CoA. HAD activity was measured after the addition of acetoacetyl-CoA to a buffer solution containing imidazole, NADH and EDTA. Absorbance of CS and HAD was recorded for 600 s, converted into enzyme activity rates, and expressed as $\mu mol \cdot g^{-1}$ $dw \cdot min^{-1}$.

### Histochemical Analysis of Capillarization and ATPase Fiber Typing

Histochemical analysis of ATPase (Brooke and Kaiser, 1970) was used to determine the fiber type composition (type 1, 2a, 2x) and fiber cross-sectional area (CSA), while the amylase periodic acid-Schiff reaction (Andersen, 1975) was applied for staining of capillaries (TEMA image analysis system; Scanbeam a/s, Hadsund, Denmark). In brief, serial sections (10 µm) of the muscle biopsies samples were cut in a cryostat at −20°C, and fiber type distribution was obtained by ATPase histochemistry analysis performed after pre-incubation at pH 4.37, 4.60, and 10.30. An average of 85 ± 16 fibers was analyzed in each biopsy. The serial sections of the various ATPases were visualized and analyzed for fiber type, using a TEMA image analyzing system (Scanbeam, Hadsund, Denmark).

### Transmission Electron Microscopy

To examine the content and subcellular localization of mitochondria and lipids, muscle biopsy specimens were prepared for TEM as described previously (Nielsen et al., 2010a,b). In the prepared sections, all longitudinal-oriented fibers (∼9 per biopsy) were photographed at x40,000 magnification in a randomized, systematic order to ensure unbiased results. From each fiber, 12 images both from the myofibrillar (six from the superficial and central region, respectively) and subsarcolemmal (SS) regions were obtained as previously described (Nielsen et al., 2010a,b). Fibers were identified as type 1 or type 2 based on a combination of mitochondrial volume fraction and z-line width as described elsewhere (Nielsen et al., 2011). In order to identify the two main fiber types, all intermediate fibers were discarded and only distinct type 1 and 2 fibers were included, respectively ($n$ = 2–3 fibers of each type per biopsy). The contents of mitochondria in the intermyofibrillar (IMF) and SS regions were estimated by point counting (Weibel, 1980, **Figure 1**). IMF mitochondria is expressed as volume fractions of the myofibrillar space and the values for the superficial region were weighted three times higher than those for the central region, to account for the cylindrical shape of the fibers, in which the superficial region (outermost half of the diameter) occupies three-quarters of the volume. The SS mitochondria are expressed as volume per surface area of the muscle fiber. The estimated coefficient of error ($_{est}$CE; see Howard and Reed, 2005) was 0.18 and 0.24 for IMF and SS mitochondria, respectively, with no difference between legs and arms. Total volume fractions of mitochondria and lipids, respectively (IMF + SS), were obtained by recalculating the SS subfractions relative to myofibrillar volume density, assuming a cylindrical shape of the fibers and a radius of 40 µm, as previously described (Nielsen et al., 2010a).

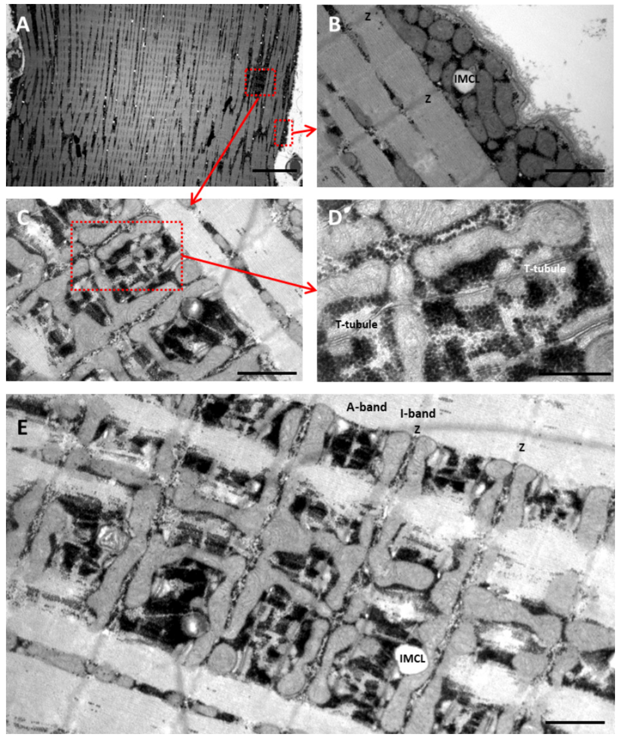


**FIGURE 1** | TEM images showing the subcellular localization of skeletal muscle mitochondria. All images are from leg muscle (*vastus lateralis*). **(A)** Overview of a part of fiber showing the myofibrillar (Myo) space and subsarcolemmal (SS) space. **(B)** The typical localization of SS mitochondria (mit) in skeletal muscle, also showing a intramyocellular lipid (IMCL). **(C)** In the Myo space, intermyofibrillar mitochondria are wrapped around the myofibrils, mainly in the I-band and often connected to an adjacent mitochondrion through the A-band. There is less marked connection between neighboring mitochondria in the I-band. **(D)** Intermyofibrillar mitochondria in the I-band on each side of the Z-line, with the t-tubular system (t-system) and mitochondria intertwined. **(E)** Overview demonstrating the IMF mitochondria are mainly located in the I-band on each side of the z-line and often connected to an adjacent mitochondrion in the same sarcomere through the A-band. All the gray structures in the fiber are mitochondria with slightly visible inner cristae. Glycogen granules can be seen as black dots. Z, Z-line; A, A-band; IMCL, intramyocellular lipid; T-tubule, transverse tubular system. Scale bar: **A**, 10 µm; **B**,**C**, 1 µm; **D**, 0.5 µm; **E**, 1 µm. Original magnification: **A**, x1,600; **B**,**C**, x20,000; **D**, x50,000; **E**, x13,000.

## Statistical Analyses

All values presented are means ± standard error of the mean (SEM) and were subjected to ANOVA test, with significant differences between means identified using the Bonferroni *post hoc* test (GraphPad Prism 6.07). All interactions or main effects were examined using a linear mixed-effects model, with the subject, limb, fiber type, and fiber as random effects and limb, fiber type, and location as fixed effects, using the Stata 10.1 software (StataCorp. 2007; Stata Statistical Software: Release 10; StataCorp LP, College Station, TX, United States). Variables exhibiting skewed distributions were log-transformed prior to analysis. The level of significance was set at $\alpha = 0.05$.

# RESULTS

## Fiber Type Distribution

The MHC distribution in the *vastus lateralis* and *triceps brachii* was the same on the left- and right-hand sides, with a significantly higher proportion of MHC-1 in the legs (58 ± 2%, range [34–69%]) than the arms (40 ± 3%, range [24–57%]) ($P < 0.01$, **Table 2**). Accordingly, the proportion of MHC-2A in the legs was lower (41 ± 2 vs. 60 ± 3%). The average MHC distribution showed a considerable variation between the skiers with MHC-1 ranging between 34–69% (leg) and 24–57% (arm) (**Table 2**). Notably, the two skiers with the highest proportion of MHC-2A in arms (70 and 72%) were successful sprint skiers.

## Enzyme Activities

The maximal CS activity of well-trained arm and leg muscles was the same (**Table 2**), despite the higher MHC-1 content of the legs, thus demonstrating a non-MHC-dependency in the CS activity. In contrast, the maximal activity of the key enzyme in the ß-oxidation, HAD, was 52% higher ($P < 0.05$) in the leg compared to arm muscles. Accordingly, the ratio between the HAD and CS activity was 45% higher in leg than arm (1.22 in the leg and 0.86 in arm, $P < 0.01$), suggesting a relatively higher capacity for lipid oxidation in leg muscle. Further, there was no association between CS activity and MHC distribution (**Figure 2A**). Thus, CS activity in these highly trained muscles is not associated with the MHC distribution. In contrast, MHC-1 content was a robust predictor of HAD capacity ($P = 0.011$, $r^2 = 0.32$, **Figure 2B**). In line with this, there was also a strong correlation between HAD/CS ratio and the MHC-1 content ($P = 0.021$, $r^2 = 0.27$), with no association in trained leg (**Figure 2C**). Taken together, in these highly trained skiers, there is a close association between MHC distribution and both absolute (HAD) and relative (HAD/CS) capacity to oxidize fat, with no association between CS capacity and MHC distribution.

## Fiber Capillarization and Size

The total number of capillaries per total number of fibers and the number of capillaries per fiber area were not different between leg and arm muscle, averaging 2.9 ± 0.1 capillaries per fiber and 417 ± 14 capillaries/mm$^2$ (**Table 3**). The average number of capillaries around each fiber was 5.8 ± 0.8 for the leg and 6.3 ± 0.3 for the arm. When considering capillaries around each fiber type, there were significantly fewer capillaries in type 2x fibers as compared with type 1 and 2a in leg muscle ($P < 0.05$, **Table 3**). There were no fiber type differences in arm muscle; however, there was a tendency toward a higher capillarization in type 2a fibers ($P = 0.078$). Further, there was a clear difference in capillarization between leg and arm muscle in type 2a fibers, with 14% more capillaries per fiber in arm muscle (**Table 3**).

The average fiber size for each fiber type and hybrid fibers, in arm and leg muscles, is shown in **Table 4**. There was no significant difference in mean fiber size between fiber types in leg muscle. However, in arm muscle, type 2a fibers were significantly larger than type 1 fibers ($P < 0.05$).

Estimation of the number of capillaries per individual fiber area in trained muscles demonstrated that type 1 fibers in both leg and arm muscles had, on average, 27% higher capillarization than type 2 fibers ($P < 0.05$), with no difference between limbs. Thus, a higher number of capillaries per fiber type 2a fibers of the arm are linked with a larger fiber size.

## Mitochondrial Content and Subcellular Localization

Transmission electron microscopy images showing the subcellular localization of skeletal muscle mitochondria in the highly trained cross-country skiers are shown in **Figure 1**, clearly demonstrating a very high mitochondrial volume in these trained muscles. The SS mitochondria were unevenly distributed below the sarcolemma, with a higher volume located near the capillaries and around the nuclei. The IMF mitochondria are wrapped around the myofibrils, mainly located on each side of the z-line. These mitochondria in the I-band are often connected to an adjacent mitochondrion in the same sarcomere through the A-band. Individual values for the total volume of mitochondria per volume of myofiber are given in **Table 5**. The total volume of mitochondria is a volume-weighted average of the superficial region and the central region of the myofiber as well as the SS space. The individual values are based on 8–12 myofibers from two different biopsies. The total mitochondrial volume averaged 8.6 ± 1.6 and 9.0 ± 2.0 $\mu m^3 \cdot \mu m^{-3}$, for the arm and leg, respectively. The relative distribution of the mitochondrial subcellular regions was estimated in a total of 29 or 30 fibers from the 10 participants. In these highly endurance-trained athletes, the skeletal muscle mitochondria had similar relative distribution between IMF and SS localizations in both leg and arm muscles and in type 1 and 2 fibers. Thus, 83–86% of the mitochondria are localized in the IMF region and 11–14% in the SS region. The mitochondrial content and subcellular localization in distinct fiber types and at the whole-muscle level of leg and arm muscles is shown in **Figure 3**. Intriguingly, there was a tendency toward (10–20%) a lower mitochondrial content in the IMF and SS regions of leg muscle fibers compared with arm muscle fibers (**Figure 3A**, $P = 0.095$). This is also apparent when calculating a total (IMF + SS) mitochondrial content (**Figure 3B**). By taking the different MHC composition of leg and arm muscles into account, the average fiber type-mitochondrial volume can be estimated, given a fiber type distribution of 57 and 37% MHC-1 in leg and arm, respectively. Weighting the fiber type distribution, the whole-muscle mitochondrial volume in leg and arm muscle was similar (**Figure 3C**). Thus, at the whole-muscle level, the non-significantly higher mitochondrial content in the arms mediated, despite a relatively higher number of MHC-2

**TABLE 2 |** The profile of myosin heavy chains and enzyme activities in the arm (*triceps brachii*) and leg (*vastus lateralis*) muscles of elite cross-country skiers ($n = 10$).

| | Fiber type distribution (% of total) | | | Enzyme activity | | |
|---|---|---|---|---|---|---|
| | **MHC-1** | **MHC-2A** | **MHC-2X** | **CS** | **HAD** | **HAD/CS** |
| Leg | 58 ± 2 | 41 ± 2 | 1.0 ± 0.4 | 118 ± 6 | 144 ± 12 | 1.22 |
| Arm | 40 ± 3* | 60 ± 3* | 0.4 ± 0.2 | 111 ± 10 | 95 ± 12* | 0.84* |

*The maximal activities of 3-hydroxy-acyl-CoA-dehydrogenase (HAD) and citrate synthase (CS) are given in μmol/g dw/min. *Significantly different from the leg muscle.*

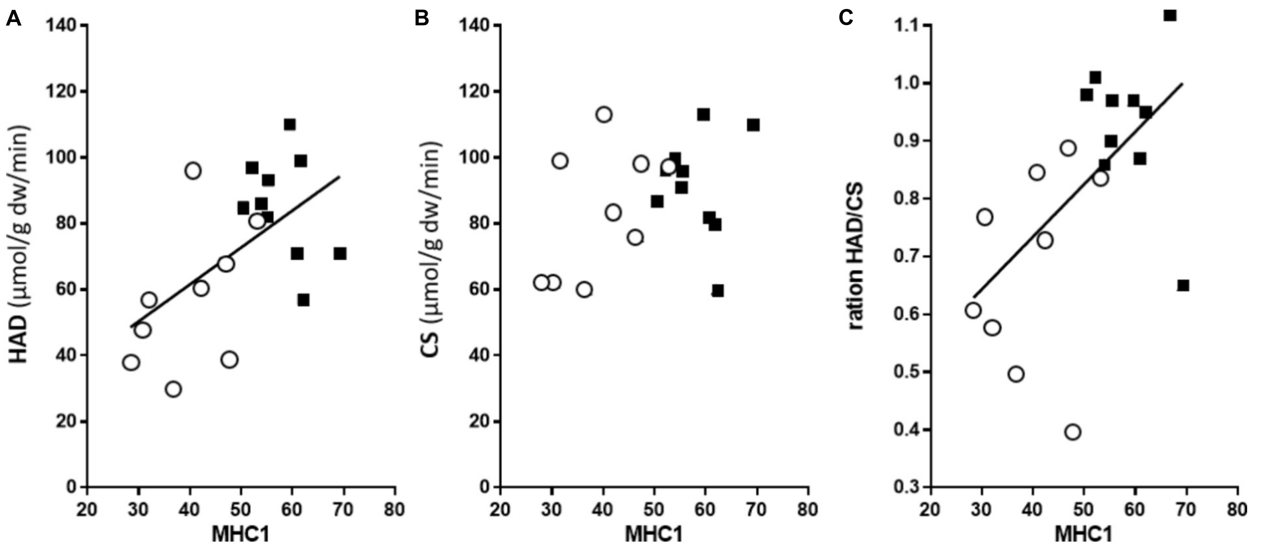


**FIGURE 2 |** The relationships between the percentage of MHC-1 and 3-hydroxyacyl-CoA dehydrogenase activity (HAD, $n = 10$) **(A)**; citrate synthase activity (CS, $n = 9$) **(B)**; and relative capacity to oxidize fat (HAD/CS ratio) **(C)**. The open circles depict data for the arms and the leg black squares for the legs. For the arm and leg combined, there was a significant correlation between the MHC-1 content and HAD activity ($r^2 = 0.32$, $P = 0.011$), as well as the HAD/CS ratio ($r^2 = 0.27$, $P = 0.021$).

**TABLE 3 |** Capillary density in the arm (*triceps brachii*) and leg (*vastus lateralis*) muscles of elite cross-country skiers ($n = 10$).

| | **#cap/fiber** | **cap/mm$^2$** | **Type 1** | **Type 2a** | **Type 2x** | **Average** |
|---|---|---|---|---|---|---|
| Leg | 2.8 ± 0.1 | 437 ± 22 | 5.9 ± 0.3 | 5.9 ± 0.2 | 5.1 ± 0.3# | 5.8 ± 0.8 |
| Arm | 3.0 ± 0.2 | 394 ± 14 | 5.8 ± 0.3 | 6.7 ± 0.3* | 6.0 ± 2.0* | 6.3 ± 0.3 |

*Capillary density was assessed immunohistochemically. Number of capillaries is given in: total number of capillaries per total number of fibers (#cap/fiber); total number of capillaries per muscle area (cap/mm$^2$), and number of capillaries around each fiber for each fiber type and average for all fibers. *Significantly different from the corresponding value for leg muscle; #significantly different from the corresponding values for the other fiber types.*

**TABLE 4 |** Fiber size in the arm (*triceps brachii*) and leg (*vastus lateralis*) muscles of elite cross-country skiers ($n = 10$).

| | **Type 1** | **Type 2a** | **Type 2x** | **Type 2a/x** |
|---|---|---|---|---|
| Leg | 5423 ± 272 | 6811 ± 297 | 6590 ± 363 | 5840 ± 518 |
| Arm | 5356 ± 200*¥¤ | 8105 ± 394* | 6125 ± 960¥ | 4576 ± 176¥ |

*Fiber size (in μm$^2$) was assessed immunohistochemically. *Significantly different from the corresponding value for leg muscle; ¥significantly different from type 2a fibers; ¤significantly different from type 2x fiber.*

fibers, an equal whole-muscle mitochondrial content in the legs and arms (**Figure 3C**). There was a significant correlation ($P = 0.02$) between the total mitochondrial content in arm muscle and whole body $VO_{2\ max}$ ($L \cdot min^{-1}$), which was not apparent in leg muscle.

## DISCUSSION

Here we compare equally trained limb muscles from elite cross-country skiers. A key finding here was that the mitochondrial volume percentage and CS activity is equal in legs and arms, despite the presence of a higher proportion of MHC-2 fibers in the arms. Furthermore, we demonstrate that well-trained type 1 and type 2 muscle fibers can have similar capillarization, regardless of whether they are located in arm or leg muscle and that the capillarization is not linked with the muscle fiber type, indicating a divergence between fiber type pattern and aerobic metabolic capacity. Also, comparable highly trained leg and arm muscles exhibited clear difference in their enzyme-linked ability to oxidize fatty acids (HAD capacity) and combined with previous data on a fourfold higher intramyocellular lipid (IMCL) volume contents in leg muscles; this points to a clear

**TABLE 5 |** The volume of mitochondria – total and in the superficial and central intermyofibrillar space (IMF) and the sarcolemmal space (SS) – in the arm and leg muscles of elite cross-country skiers ($n$ = 10).

| Participant | Arm (*triceps brachii*) | | | | Leg (*vastus lateralis*) | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | $IMF_{Superficial}$ | $IMF_{Central}$ | SS | Total | $IMF_{Superficial}$ | $IMF_{Central}$ | SS |
| 1 | 9.7 | 10.2 | 4.1 | 0.21 | – | – | – | – |
| 2 | 10.1 | 9.8 | 5.2 | 0.28 | 7.1 | 6.6 | 4.4 | 0.20 |
| 3 | 12.7 | 11.5 | 5.8 | 0.53 | 9.4 | 9.2 | 4.3 | 0.29 |
| 4 | 9.4 | 9.0 | 2.9 | 0.38 | 9.1 | 7.9 | 4.6 | 0.41 |
| 5 | 8.1 | 6.7 | 5.3 | 0.34 | 8.1 | 7.9 | 4.4 | 0.23 |
| 6 | 5.6 | 5.8 | 2.4 | 0.13 | 6.2 | 5.7 | 3.6 | 0.21 |
| 7 | 7.4 | 6.8 | 5.5 | 0.19 | 9.3 | 9.2 | 4.7 | 0.25 |
| 8 | 10.6 | 10.1 | 4.7 | 0.36 | 11.8 | 11.0 | 7.0 | 0.37 |
| 9 | 8.6 | 7.6 | 5.9 | 0.29 | 8.8 | 8.9 | 3.9 | 0.24 |
| 10 | 8.0 | 7.7 | 2.4 | 0.33 | 7.6 | 6.9 | 4.5 | 0.25 |
| Mean | 9.0 | 8.5 | 4.4 | 0.31 | 8.6 | 8.1 | 4.6 | 0.27 |
| SD | 2.0 | 1.9 | 1.4 | 0.11 | 1.6 | 1.6 | 1.0 | 0.07 |

*Total, total volume of mitochondria per volume of myofiber; $IMF_{superficial}$, intermyofibrillar mitochondrial volume per volume of myofibrillar space in the superficial region of the myofiber; $IMF_{central}$, intermyofibrillar mitochondrial volume per volume of myofibrillar space in the central region of the myofiber; SS, subsarcolemmal mitochondrial volume per area of myofiber surface. The individual values presented are the means for 8–12 myofibers in biopsies taken before and 22 h after the race. All data are given in volume densities ($\mu m^3\ \mu m^{-3}$), except in the case of SS, where they are volume per SS area ($\mu m^3 \cdot \mu m^{-2}$).*

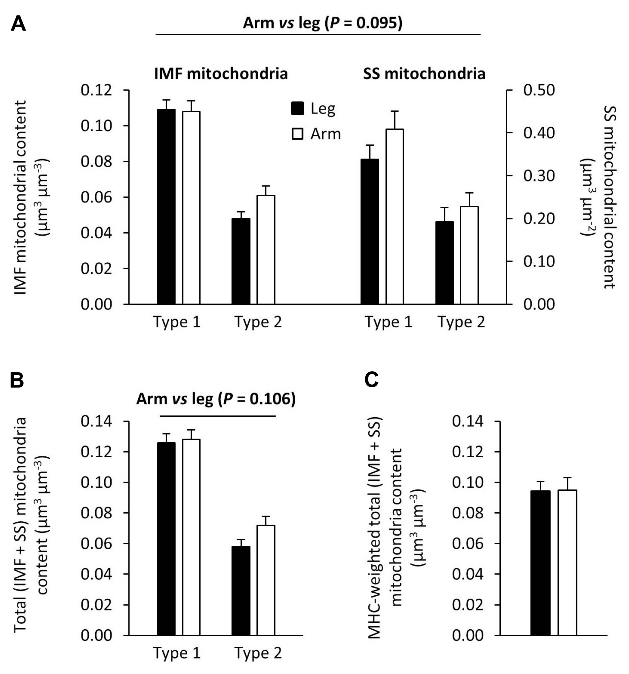


**FIGURE 3 |** Mitochondria content and subcellular localization in distinct fiber types and at whole-muscle level of leg and arm muscles. There was a tendency ($P$ = 0.095) toward a higher mitochondrial content in the intermyofibrillar (IMF) and subsarcolemmal (SS) regions, of arm muscle (open bars) compared with leg muscle (filled bars) **(A)**. This tendency is also apparent when calculating total mitochondrial content (IMF + SS) **(B)**. **(C)** Weighted mitochondrial volumes in the arm and leg muscle, estimated from a fiber type distribution of 57 and 37% MHC-I for the leg and arm ($n$ = 9), respectively. These MHC weighted values of whole-muscle mitochondrial content in arm and leg muscles are similar. Values are means ± SE ($n$ = 29–30 fibers from 10 subjects).

limb difference in fat metabolism between the leg and the arm, which cannot be explained by the different fiber type distributions.

## Fiber Type Malleability

In order to fulfill various functional needs, different skeletal muscle fiber types express different molecular isoforms of myosin. The contractile characteristics of the given muscle fiber type are generally considered as being linked with metabolic and $Ca^{2+}$ handling properties, with fibers expressing MHC-1 having the highest oxidative capacity while being slow to shorten and having slower $Ca^{2+}$ handling, with MHC-2 fibers having the opposite characteristics. This was demonstrated very clearly in the early studies by Burke et al. (1971), who showed a phenotypic characterization of quite strict links between contractile function and metabolic profile in that type 2 fibers are glycolytic, while type 1 fibers are oxidative. Despite several reports indicative of plasticity in this relationship, this long-held concept is still the reigning dogma. In later studies on humans, more evidence has been provided on the large plasticity of all fiber types with respect to their aerobic potential despite no or only a small transformation of the type 2a to the type 1 isoform (Holloszy, 1967; Hoppeler and Fluck, 2003; Schiaffino and Reggiani, 2011). In line with this, Essén et al. (1975) reported an equally high SDH activity in the type 2 and type 1 muscle fibers in top endurance runners [with a maximal oxygen uptake ($\dot{V}O_{2max}$) > 72 ml·kg$^{-1}$·min$^{-1}$], with untrained having a clear fiber type difference with only half the SDH activity in their type 2 muscle fibers. Also, the mitochondrial volume density is generally considered to be strongly fiber type-dependent. In untrained humans, the mitochondrial volume varies from 6% in type I fibers to 4.5% in type 2a and 2.3% in type 2x fibers

(Howald et al., 1985), with a more pronounced difference in animal studies of oxidative and glycolytic muscle, i.e., 2.7 times higher in rabbits and 4.5 times higher in rats (Saltin and Gollnick, 1983; Jackman and Willis, 1996). In the current study, we compared equally trained arm and leg muscle based on the same CS activity (**Table 2**), the same average capillarization (**Table 3**), and no difference in the mitochondrial content at whole-muscle level. Based on this, we state that arm and leg muscle are equally trained. In these endurance-trained humans, there is a twofold higher mitochondrial volume density between type 1 and 2 fibers (**Figure 3**). Furthermore, the volume density of the type 2 fibers from trained is equal to (Howald et al., 1985) or higher (Nielsen et al., 2010a) than in type 1 fibers from untrained individuals. Thus, fiber type mitochondrial content is extremely malleable with muscle activity and inactivity (Hoppeler, 1986; Nielsen et al., 2010b). These changes in fiber metabolic characteristics are clearly not fiber-type-dependent, and a considerable variation exists within each fiber type with a clear overlay between fiber types. In line with this, a recent study indicated that type 2a fibers can possess equally high or even higher mitochondrial respiration as type 1 fibers (Boushel et al., 2014). The equal volume density of mitochondria and CS activity in different types of fibers suggest that the intrinsic characteristics of mitochondria are variable and not determined solely by fiber type.

Here we report that the metabolic profile of muscle fibers varies with no change in the myosin isoform they express. Thus, in highly trained humans, the mitochondrial volume percentage is equal in the arms and legs, despite a relatively higher number of MHC-2 fibers in arms, and type 2A fibers from the arm being larger, with the same number of capillaries per fiber area. In these highly trained skiers, the type 2 fibers have an equally high oxidative capacity as type 1 fibers, demonstrating that the metabolic profile of a given fiber isoform displays considerable plasticity. Interestingly, we have previously reported in the same subjects, an approximate 4.6-fold higher SR $Ca^{2+}$ release rate in MHC 2 fibers compared to MHC 1 (Ørtenblad et al., 2011). As SR $Ca^{2+}$ handling is a key component in the development of fatigue during most types of exercise, it is physiologically crucial for these skiers to possess a high SR $Ca^{2+}$ uptake and release rate (Ørtenblad et al., 2000a; Gejl et al., 2014). These data on trained skiers suggest a new perspective on fiber types, indicating a divergence between MHC isoform pattern and aerobic metabolic capacity, with a high variability in the metabolic profile, closely related to the usage of the muscle fiber, within the various MHC isoforms. Thus, these highly trained skiers possess a type 2 fiber which is highly oxidative, has an equal CS activity as type 1 fibers, has a larger CSA, with the same capillarization per CSA, while having a near fivefold higher SR $Ca^{2+}$ handling capacity than type 1 fibers. In all, these findings represent a muscle fiber with high force and power properties, while having a highly developed endurance capacity to fulfill the demands of today's elite cross-country skier requiring the combined ability to generate and sustain rapid, prolonged high force production during short contacts with the ground (Holmberg, 2015; Andersson et al., 2016).

## Mitochondrial Subcellular Distribution and Volume Fraction

The current data from arm and leg muscles drawn from the elite endurance-trained subjects revealed that type 1 and 2 fibers have the same relative subcellular distribution of mitochondria. Thus, around 85% of the muscle mitochondria are located in the IMF region and the remainder in the SS region, regardless of fiber type and limb. This is in line with a training study showing that type 1 and 2 fibers have similar relative distribution of mitochondria after training (Howald et al., 1985).

The mitochondrial volume fraction was not different between limbs, averaging 9.5%. The reported mitochondrial volume fraction is ∼20–30% higher than found in previously reported short-term training studies (Howald et al., 1985; Nielsen et al., 2010a) as well as in endurance-trained athletes (Hoppeler, 1986). However, a mitochondrial volume percentage of 11.4% in *vastus lateralis* for a similar group of highly trained athletes, i.e., professional cyclists ($n$ = 3), has been reported (Hoppeler, 1986). In these athletes, *vastus lateralis* played a more primary role in performance than in cross-country skiing, explaining the greater necessity for mitochondria in that particular muscle. The mitochondrial volume fraction of 9.5% in trained skiers is about two times larger than previously reported in untrained individuals using the same method (Nielsen et al., 2010a), and is in line with data showing a two to two-and-a-half fold higher activity of key mitochondrial enzyme (SDH, CS, and HAD) activity in trained cross-country skiers than observed in sedentary individuals (Gollnick et al., 1972; Saltin, 1996). In addition to mitochondrial distribution and volume percentage of the cell and mitochondrial enzymes, there may be other differences in mitochondria network, shape, topology, or function between fiber types, limbs, and human populations (Nielsen et al., 2017).

## Mitochondrial Content and Distribution in Leg Versus Arm

Weighing the different fiber type distribution in leg and arm muscle, the mitochondrial volume fraction was equal in both (**Figure 3D**). This suggests that arm muscles, despite lower fat oxidation capacity (Helge, 2010), HAD activity (present data), lower IMCL content (Koh et al., 2017), and higher lactate release during exercise (Van Hall et al., 2003), still require a high mitochondrial oxidative capacity. Indeed, there was a tendency ($P$ = 0.095) toward a 10% higher mitochondrial volume fraction in the fibers from the arms compared with the legs (**Figure 3C**), predominantly due to a tendency to higher volume fraction in type 2 fibers in the arms (**Figure 3C**). Thus, differences in leg and arm whole-muscle metabolic characteristics may not solely be explained by the dissimilar fiber type distribution in the limbs. The high mitochondrial content in type 2 fibers in arm could either be a consequence of the high metabolic demand in the upper body of these trained subjects or, possibly, due to a high demand for glycolytic flux in type 2 fibers. Thus, there is a clear necessity for being able to convert lactate to pyruvate within the mitochondrial intermembrane space with pyruvate subsequently taken into the mitochondrial matrix where it enters the TCA cycle and is ultimately oxidized (Brooks et al., 1999;

Hashimoto et al., 2006; Jacobs et al., 2013). Furthermore, peak arm blood flow and $O_2$ delivery per unit muscle mass during arm exercise is higher than that to leg muscle during leg cycling reflecting the proportional matching of oxygen delivery to oxidative capacity (Boushel et al., 2011).

The present study design involved a pair-wise comparison of equally highly trained muscles from the same individual subjects, who had trained systematically for 11 years on average and whose muscle mitochondrial volume fractions are among the highest ever reported. A cross-sectional comparison of, e.g., kayakers or cyclists who train their upper or lower bodies specifically, would have allowed characterization of more highly trained muscles, for instance, with more extensive local blood flow during exercise. However, higher mitochondrial volume fractions have not been reported in larger groups and a cross-sectional design would limit direct comparisons between limbs. At the same time, it is important to note that our present observations and conclusions are relevant only for equally well-trained arm and leg muscles.

## Intramyocellular Lipid (IMCL) Content and Subcellular Localization

We have recently reported in a companion paper (Koh et al., 2017) that, in these subjects with highly trained upper and lower body, the IMCL volume fraction was fourfold higher in leg muscle than in the arm muscle. The higher content of IMCL content was apparent in both the IMF and the SS regions. Additionally, there was a fiber type specific difference in IMCL volume fractions, with a threefold higher IMF ($P$ = 0.0002) and total ($P$ = 0.0003) lipid droplet volume fractions in type 1 fibers than in type 2 fibers, while no difference was found between the fiber types ($P$ = 0.6) in the SS lipid droplet volume fraction. The fourfold lower IMCL content of the arms compared to the leg cannot solely be explained by the higher proportion of MHC-2 fibers of arm, so a true intrinsic limb difference in fat metabolism must exist. The higher IMCL content of the leg muscle compared with the arm muscle is in accordance with the lower fat oxidation capacity of arm muscle (Helge, 2010) and the notion that exercising arm muscle evidently has a lower fat oxidation compared to leg muscle (Calbet et al., 2005; Helge, 2010).

The high content of IMCL in skeletal muscle of trained subjects and obese type 2 diabetics has been described as “the athlete paradox” (Goodpaster et al., 2001). However, the current data are in accordance with a new perspective on this apparent paradox, suggesting that the elevated IMCL content found in both type 2 diabetic patients (Nielsen et al., 2010a) and endurance-trained athletes (Koh et al., 2017) is an average of differential subcellular distribution of IMCL, where athletes have elevated IMF and type 2 diabetes patients elevated SS IMCL (Nielsen et al., 2010a). Thus, the roles of IMF and SS IMCL in skeletal muscle glucose regulation are most likely fiber type and training status specific.

## Enzyme Activities

In our highly trained cross-country skiers, with equally and exceptionally well-trained leg and arm muscle, there was a 52% higher HAD capacity in the leg compared to arm muscles and the ratio between the HAD and CS activity was 1.22 in the leg and 0.86 in arm, suggesting a relatively higher capacity for lipid oxidation in leg muscle. These enzyme activity data demonstrate a very good agreement with the four-fold higher IMCL in the leg compared to the arm muscle. Notably, the MHC-1 content was a very strong predictor of HAD activity in trained arm ($r^2$ = 0.69), with no association in leg muscle. This clear limb difference in the association between fiber MHC distribution and HAD capacity was not apparent with CS activity, depending rather on other factors as, i.e., training-induced adaptations. Taken together, there is a clear limb difference in HAD and HAD/CS ratio, with legs having a non-MHC dependent capacity to oxidize fat, while in arm muscle, there is a very close association between MHC distribution and both absolute (HAD activity) and relative capacity to oxidize fat (HAD/CS). This supports the notion that the upper body has a lower capacity to oxidize fat and a lower fat oxidation during the same relative intensity compared to leg muscle (Calbet et al., 2005; Helge, 2010). This lower capacity to oxidize fat and higher reliance on CHO oxidation in the upper body compared to the lower body is irrespective of limb training status, and persistent also in highly trained cross country skiers with equally trained arm and leg muscle.

# CONCLUSION AND PERSPECTIVES

Here, we show that in highly trained muscles of elite cross-country skiers, the mitochondrial volume percentage as well as the number of capillaries per fiber area are the same in the arms and legs, despite the presence of relatively more MHC-2 fibers and larger type 2A fibers in the arms. Thus, the metabolic profile of muscle fibers can vary without any change in the myosin isoform they express. These findings provide a new perspective, with a divergence between fiber type and aerobic metabolic capacity, and considerable variability in the metabolic profile of the various MHC-isoforms which is closely related to the usage of the muscle fiber. Our well-trained cross-country skiers have developed highly oxidative type 2 muscle fibers capable of producing great force and power in order to meet today’s need for pronounced endurance in combination with rapid generation of large forces during short contact periods.

We also demonstrate that leg and arm muscles exhibit a clear difference in their IMCL content and distribution, as well as in the ability to oxidize fatty acids. The observed difference in IMCL content in the upper and lower body cannot be explained by training status of the involved muscles or the different fiber type distribution in the limbs. This implies that the capacity to oxidize and store IMCL is clearly higher in leg compared with arm muscle, even though limbs are equally highly trained and express similar mitochondrial content and capillarization. In line with this, the HAD activity and the HAD/CS ratio were significantly higher in leg muscle. Thus, it is evident that limbs have different lipid metabolism independent of fiber type differences.

## AUTHOR CONTRIBUTIONS

NØ, JN, H-CH, and BS were involved in the study design. NØ, JN, H-CH, KS, and BS have collected the data. All authors contributed to interpretation of data and drafting of the manuscript and all but BS have reviewed the final version of the submitted manuscript. BS passed away before the final approval of the manuscript. Transmission electron microscopy measurements were performed by JN at the Department of Pathology, Odense University Hospital, Denmark.

## FUNDING

This work was supported by funds from the Danish Ministry of Culture Committee on Sports Research, Swedish National Centre for Sports Research and Copenhagen Muscle Research Centre, and the Natural Science and Engineering Council of Canada.

## REFERENCES

Andersen, P. (1975). Capillary density in skeletal muscle of man. *Acta Physiol. Scand.* 95, 203–205. doi: 10.1111/j.1748-1716.1975.tb10043.x

Andersson, E., Holmberg, H. C., Ørtenblad, N., and Björklund, G. (2016). Metabolic responses and pacing strategies during successive sprint skiing time trials. *Med. Sci. Sports Exerc.* 48, 2544–2554. doi: 10.1249/MSS.0000000000001037

Boushel, R., Ara, I., Gnaiger, E., Helge, J. W., González-Alonso, J., Munck-Andersen, T., et al. (2014). Low intensity training increases peak arm $VO_2$ by enhancing both convective and diffusive $O_2$ delivery. *Acta Physiol.* 211, 122–134. doi: 10.1111/apha.12258

Boushel, R., Ggaiger, E., Wright-Paradis, C., Calbet, J. A., Gonzales-Alonso, J., Munck- Andersen, T., et al. (2011). Muscle mitochondrial capacity exceeds maximal oxygen delivery in humans. *Mitochondrion* 11, 303–307. doi: 10.1016/j.mito.2010.12.006

Brooke, M. H., and Kaiser, K. K. (1970). Three "myosin adenosine triphosphatase" systems: the nature of their pH lability and sulfhydryl dependence. *J. Histochem. Cytochem.* 18, 670–672. doi: 10.1177/18.9.670

Brooks, G. A., Dubouchaud, H., Brown, M., Sicurello, J. P., and Butz, C. E. (1999). Role of mitochondrial lactate dehydrogenase and lactate oxidation in the intracellular lactate shuttle. *Proc. Natl. Acad. Sci. U.S.A.* 96, 1129–1134. doi: 10.1073/pnas.96.3.1129

Burke, R. E., Levine, D. N., and Zajac, F. E. III (1971). Mammalian motor units: physiological-histochemical correlation in three types in cat gastrocnemius. *Science* 174, 709–712. doi: 10.1126/science.174.4010.709

Calbet, J. A., Holmberg, H. C., Rosdahl, H., van Hall, G., Jensen-Urstad, M., and Saltin, B. (2005). Why do arms extract less oxygen than legs during exercise? *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 289, R1448–R1458. doi: 10.1152/ajpregu.00824.2004

Canepari, M., Pellegrino, M. A., D'Antona, G., and Bottinelli, R. (2010). Skeletal muscle fiber diversity and the underlying mechanisms. *Acta Physiol.* 199, 465–476. doi: 10.1111/j.1748-1716.2010.02118.x

Essén, B., Jansson, E., Henriksson, J., Taylor, A. W., and Saltin, B. (1975). Metabolic characteristics of fiber types in human skeletal muscle. *Acta Physiol.* 95, 153–165. doi: 10.1111/j.1748-1716.1975.tb10038.x

Gejl, K., Hvid, L. G., Ulrik Frandsen, U., Jensen, K., Sahlin, K., and Ørtenblad, N. (2014). Muscle glycogen content modifies SR $Ca_2{}^+$ release rate in elite endurance athletes. *Med. Sci. Sports Exerc.* 46, 496–505. doi: 10.1249/MSS.0000000000000132

Gollnick, P. D., Armstrong, R. B., Saubert, C. W. IV, Piehl, K., and Saltin, B. (1972). Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. *J. Appl. Physiol.* 33, 312–319. doi: 10.1152/jappl.1972.33.3.312

Goodpaster, B. H., He, J., Watkins, S., and Kelley, D. E. (2001). Skeletal muscle lipid content and insulin resistance: evidence for a paradox in endurance-trained athletes. *J. Clin. Endocrinol. Metab.* 86, 5755–5761. doi: 10.1210/jcem.86.12.8075

Hashimoto, T., Hussien, R., and Brooks, G. A. (2006). Colocalization of MCT1, CD147, and LDH in mitochondrial inner membrane of L6 muscle cells: evidence of a mitochondrial lactate oxidation complex. *Am. J. Physiol.* 290, E1237–E1244. doi: 10.1152/ajpendo.00594.2005

Helge, J. W. (2010). Arm and leg substrate utilization and muscle adaptation after prolonged low-intensity training. *Acta Physiol.* 199, 519–528. doi: 10.1111/j.1748-1716.2010.02123.x

Holloszy, J. O. (1967). Biochemical adaptations in muscle. Effects of exercise on mitochondrial oxygen uptake and respiratory enzyme activity in skeletal muscle. *J. Biol. Chem.* 242, 2278–2282.

Holmberg, H. C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scand. J. Med. Sci. Sports Suppl.* 4, 100–109. doi: 10.1111/sms.12601

Holmberg, H. C., Lindinger, S., Stöggl, T., Eitzlmair, E., and Muller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sports Exerc.* 37, 807–818. doi: 10.1249/01.MSS.0000162615.47763.C8

Hoppeler, H. (1986). Exercise-induced ultrastructural changes in skeletal muscle. *Int. J. Sports Med.* 7, 187–204. doi: 10.1055/s-2008-1025758

Hoppeler, H., and Fluck, M. (2003). Plasticity of skeletal muscle mitochondria: structure and function. *Med. Sci. Sports Exerc.* 35, 95–104. doi: 10.1097/00005768-200301000-00016

Howald, H., Hoppeler, H., Claassen, H., Mathieu, O., and Straub, R. (1985). Influence of endurance training on the ultrastructure composition of different muscle fiber types in humans. *Pflügers Arch.* 403, 369–376. doi: 10.1007/BF00589248

Howard, C. V., and Reed, M. G. (2005). *Unbiased Stereology. Three-Dimensional Measurement in Microscopy*. Oxford: Bios Scientific Publishers.

Jackman, M. R., and Willis, W. T. (1996). Characteristics of mitochondria isolated from type I and type IIb skeletal muscle. *Am. J. Physiol.* 270, C673–C678. doi: 10.1152/ajpcell.1996.270.2.C673

Jacobs, R. A., Meinild, A. K., Nordsborg, N. B., and Lundby, C. (2013). Lactate oxidation in human skeletal muscle mitochondria. *Am. J. Physiol.* 304, E686–E694. doi: 10.1152/ajpendo.00476.2012

Koh, H.-C. E., Nielsen, J., Saltin, B., Holmberg, H.-C., and Ørtenblad, N. (2017). Pronounced limb and fibre type differences in subcellular lipid droplet content and distribution in elite skiers before and after exhaustive exercise. *J. Physiol.* 595, 5781–5795. doi: 10.1113/JP274462

Komi, P. V., and Norman, R. W. (1987). Preloading of the thrust phase in cross-country skiing. *Int. J. Sports Med.* 8(Suppl. 1), 48–54. doi: 10.1055/s-2008-1025703

Lowry, O. H., and Passonneau, J. V. (1972). *A Flexible System on Enzymatic Analysis*. New York, NY: Academic Press.

Nielsen, J., Gejl, K. D., Hey-Mogensen, M., Holmberg, H. C., Suetta, C., Krustrup, P., et al. (2017). Plasticity in mitochondrial cristae density allows metabolic capacity modulation in human skeletal muscle. *J. Physiol.* 595, 2839–2847. doi: 10.1113/JP273040

Nielsen, J., Holmberg, H. C., Schrøder, H. D., Saltin, B., and Ørtenblad, N. (2011). Human skeletal muscle glycogen utilization in exhaustive exercise: role of subcellular localization and fiber type. *J. Physiol.* 589, 2871–2885. doi: 10.1113/jphysiol.2010.204487

Nielsen, J., Mogensen, M., Vind, B. F., Sahlin, K., Hojlund, K., Schrøder, H. D., et al. (2010a). Increased subsarcolemmal lipids in type 2 diabetes: effect of training on localization of lipids, mitochondria, and glycogen in sedentary human skeletal muscle. *Am. J. Physiol.* 298, E706–E713. doi: 10.1152/ajpendo.00692.2009

Nielsen, J., Suetta, C., Hvid, L. G., Schrøder, H. D., Aagaard, P., and Ørtenblad, N. (2010b). Subcellular localization dependent decrements in skeletal muscle glycogen and mitochondria content following short-term disuse in young and old men. *Am. J. Physiol.* 299, E1053–E1060. doi: 10.1152/ajpendo.00324.2010

Ørtenblad, N., Lunde, P. K., Levin, K., Andersen, J. L., and Pedersen, P. K. (2000a). Enhanced sarcoplasmic reticulum $Ca_2{}^+$ release following intermittent sprint-training. *Am. J. Physiol.* 279, R152–R160. doi: 10.1152/ajpregu.2000.279.1.R152

Ørtenblad, N., Nielsen, J., Saltin, B., and Holmberg, H. C. (2011). Role of glycogen availability in sarcoplasmic reticulum $Ca_2^+$ kinetics in human skeletal muscle. *J. Physiol.* 589, 711–725. doi: 10.1113/jphysiol.2010.195982

Ørtenblad, N., Sjøgaard, G., and Madsen, K. (2000b). Impaired sarcoplasmic retibulum $Ca_2^+$ release following fatiguing stimulation in rat skeletal muscle. *J. Appl. Physiol.* 89, 210–217. doi: 10.1152/jappl.2000.89.1.210

Saltin, B. (1996). "The physiology of competitive c.c. skiing across a four decade perspective; with a note on training induced adaptations and role of training at medium altitude," in *Science and Skiing*, eds E. Müller, H. Schwameder, E. Kornex, and C. Raschner (Cambridge: Chapman and Hall), 435–469.

Saltin, B., and Gollnick, P. D. (1983). "Skeletal muscle adaptability: significance for metabolism and performance," in *Handbook of Physiology, Skeletal Muscle*, eds L. D. Peachey, R. H. Adrian, and S. R. Gaiger (Bethesda, MD: American Physiological Society), 555–631.

Schiaffino, S., and Reggiani, C. (2011). Fiber types in mammalian skeletal muscles. *Physiol. Rev.* 91, 1447–1531. doi: 10.1152/physrev.00031.2010

Stephenson, D. G., Lamb, G. D., and Stephenson, G. M. (1998). Events of the excitation-contraction-relaxation (E-C-R) cycle in fast- and slow-twitch mammalian muscle fibers relevant to muscle fatigue. *Acta Physiol. Scand.* 162, 229–245. doi: 10.1046/j.1365-201X.1998.0304f.x

Van Hall, G., Jensen-Urstad, M., Rosdahl, H., Holmberg, H. C., Saltin, B., and Calbet, J. A. (2003). Leg and arm lactate and substrate kinetics during exercise. *Am. J. Physiol.* 284, E193–E205.

Weibel, E. R. (1980). *Stereological Methods: Theoretical Foundations*, Vol. 2. London: Academic Press.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

PERSPECTIVE
published: 24 July 2018
doi: 10.3389/fphys.2018.00976

# Developments in the Biomechanics and Equipment of Olympic Cross-Country Skiers

*Barbara Pellegrini[1,2]*, Thomas Leonhard Stöggl[3] and Hans-Christer Holmberg[4,5]*

[1] CeRiSM Research Centre "Mountain, Sport, and Health," Rovereto, Italy, [2] Department of Neuroscience, Biomedicine and Movement Sciences, University of Verona, Verona, Italy, [3] Department of Sport Science and Kinesiology, University of Salzburg, Salzburg, Austria, [4] The Swedish Winter Sports Research Centre, Mid Sweden University, Östersund, Sweden, [5] School of Sport Sciences, UiT – The Arctic University of Norway, Tromsø, Norway

Here, our aim was to describe the major changes in cross-country (XC) skiing in recent decades, as well as potential future developments. XC skiing has been an Olympic event since the very first Winter Games in Chamonix, France, in 1924. Over the past decades, considerable developments in skiing techniques and improvements in equipment and track preparation have increased skiing speed. In contrast to the numerous investigations on the physiological determinants of successful performance, key biomechanical factors have been less explored. Today's XC skier must master a wide range of speeds, terrains, and race distances and formats (e.g., distance races with individual start, mass-start or pursuit; knock-out and team-sprint; relays), continuously adapting by alternating between various sub-techniques. Moreover, several of the new events in which skiers compete head-to-head favor technical and tactical flexibility and encourage high-speed techniques (including more rapid development of propulsive force and higher peak forces), as well as appropriate training. Moreover, the trends toward more extensive use of double poling and skiing without grip wax in classical races have given rise to regulations in connection with Olympic distances that appear to have preserved utilization of the traditional classical sub-techniques. In conclusion, although both XC equipment and biomechanics have developed significantly in recent decades, there is clearly room for further improvement. In this context as well, for analyzing performance and optimizing training, sensor technology has a potentially important role to play.

**Keywords: performance, pole, poling force, ski, skiing technique, track preparation**

OPEN ACCESS

***Edited by:***
*Gregoire P. Millet,*
*Université de Lausanne, Switzerland*

***Reviewed by:***
*Romuald Lepers,*
*Université de Bourgogne, France*
*Antonio La Torre,*
*Università degli Studi di Milano, Italy*

****Correspondence:***
*Barbara Pellegrini*
*barbara.pellegrini@univr.it*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *26 April 2018*
***Accepted:*** *03 July 2018*
***Published:*** *24 July 2018*

***Citation:***
*Pellegrini B, Stöggl TL and Holmberg H-C (2018) Developments in the Biomechanics and Equipment of Olympic Cross-Country Skiers. Front. Physiol. 9:976. doi: 10.3389/fphys.2018.00976*

## INTRODUCTION

In modern times, from the first 1924 Winter Olympics Games in Chamonix to those in Pyeongchang, South Korea, in 2018, cross-country (XC) skiing is the sport that has probably evolved most, including new race formats, improved equipment and preparation of tracks and extensive changes in technique. In addition to being one of the most physiologically demanding endurance sports (Hoffman and Clifford, 1992; Holmberg, 2015), XC skiing also involves highly complex biomechanics (Smith, 1990). Since propulsive force is produced by the musculature of both the upper and lower body and transmitted to the ground via the skis and poles, XC skiing can be viewed as involving a four-limbed gait, which is rather uncommon for predominantly bipedal humans (Pellegrini et al., 2014).

The traditional classical style includes four different sub-techniques, i.e., diagonal skiing (DS), double poling (DP), double poling with a kick (DK), and the herringbone technique (HB) (Nilsson et al., 2004). During the 1980s, skating, more economical and approximately 10–20% faster than the classical style (Conconi et al., 1983; Karvonen et al., 1987; Pinchak et al., 1987; Fredrick and Street, 1988), was introduced and since 1988, has become an official style for competitive XC ski racing. Skating consists of five different sub-techniques (Holmberg, 1996; Nilsson et al., 2004), between which skiers switch in response to changes in speed and slope and which can, accordingly, be considered to represent a gear system (Holmberg, 1996; Nilsson et al., 2004). Clearly, selection of the appropriate technique may exert an important influence on locomotor efficiency and performance (Kvamme et al., 2005; Andersson et al., 2010; Pellegrini et al., 2013; Stöggl et al., 2018). In fact, XC skiing is still evolving, with both small and more pronounced alterations in existing skiing techniques, as well as development of novel sub-techniques.

The aim of the present perspective was to describe and discuss the major changes in XC skiing in recent decades, as well as potential future developments.

## EVOLUTION OF RACE FORMATS AND SKI TRACKS

Over the past three decades, several new race formats designed to enhance the popularity of competitive XC skiing have been introduced – the pursuit at the 1992 Olympic Games in Albertville, the mass-start and sprint at Salt Lake City in 2002, the Skiathlon at Vancouver in 2010 and the team sprint at Torino in 2006 (**Figure 1**). A total of 10 of the 12 events involve head-to-head competition, previously associated only with relays. All of these events make great demands on high speed and require extensive alterations in velocity during a race, as well as achievement and maintenance of high finishing velocity (Sandbakk and Holmberg, 2014). Thus, they challenge both technical and tactical competence [e.g., positioning or drafting behind other skiers on flatter portions of the course (Bilodeau et al., 1994)].

According to the manual of the Fédération International de Ski (FIS, 2012), a course should test the skier's technical and physical abilities while providing smooth transitions between approximately equal lengths of uphill, downhill, and undulating terrain. Recently, tracks are being designed to include multiple shorter laps for better presentation to spectators at the stadium, as well as via television and other media.

The use of snow guns, which began in the 1990s in regions with little snow, expanded in the 2000s and today most World Cup and Olympic XC ski races are held on a combination of natural and artificial snow (E. Macor, personal communication, April 20, 2018) the latter often also being used as a base. The macro- and micro-structures of natural snow are complex and can vary extensively under different environmental conditions (Karlöf et al., 2013). In contrast, artificial snow is generally less variable, providing a harder surface that allows strong pushes without deep penetration by the poles or skis and, furthermore, lasts longer without melting or deteriorating from usage. Snow-grooming machines have also been developed significantly, providing harder and more homogenous surfaces that allow faster skiing.

## EVOLUTION OF EQUIPMENT

Ekström (1980) has described skiing as "a relationship between man, equipment and environment and all these factors should be adapted to each other to obtain an optimal result." More formally, a skier's motion is determined by the balance between propulsive and resistive forces (i.e., aerodynamic drag, gravitational pull while skiing uphill, and friction between ski and snow). Ski-snow friction and drag constitute approximately 30 and 15% of the energy cost, respectively (Spring et al., 1988). Thus, greater power and better economy can be achieved by maximizing propulsive and minimizing resistive forces, a simple fact that has guided the evolution of ski equipment. Because of its complexity, the wide range of speeds (5–70 km/h) and terrain (inclines of −20 to 20%) (Sandbakk and Holmberg, 2014), technique and equipment exert a pronounced impact on skiing.

### Skis and Bindings

From originally being made of wood, since the 1970s XC skis are constructed of polyethylene plastic, fiberglass, and carbon fiber. Olympic skiers have 30–50 pairs (< 25% of which are used in most races) (H-C Holmberg, personal communication, 30 March, 2018), each designed for specific snow temperatures and conditions (Breitschädel, 2012). Sintered thermoplastics have become the standard base material, allowing new processes and treatments that have lowered the friction coefficient substantially (Breitschädel, 2015). At present, 10–15 bases with characteristics specific for various snow conditions are used by elite skiers (Holmberg, 2018). Appropriate preparation of the ski base surface by stone grinding (Breitschädel, 2015) improves gliding substantially. In addition, various glide and grip waxes tailored for different snow conditions further enhance performance. In this context, hydrophobic fluorinated waxes repel moisture, thereby reducing wet friction significantly. During the final ski preparation, various hand-held tools are frequently employed to create different microstructures. In recent years, considerable work and technological development have been devoted to precise characterization of friction during skiing (Breitschädel et al., 2010; Swarén et al., 2014; Budde and Himes, 2017), with the aim of optimizing preparation and waxing. National teams now spend considerable money on highly specialized staff who prepares the skis and all major nations have designated waxing trailers where preparation can be optimized.

For modern skis, the coefficient of friction, which exerts considerable impact on the total mechanical work required

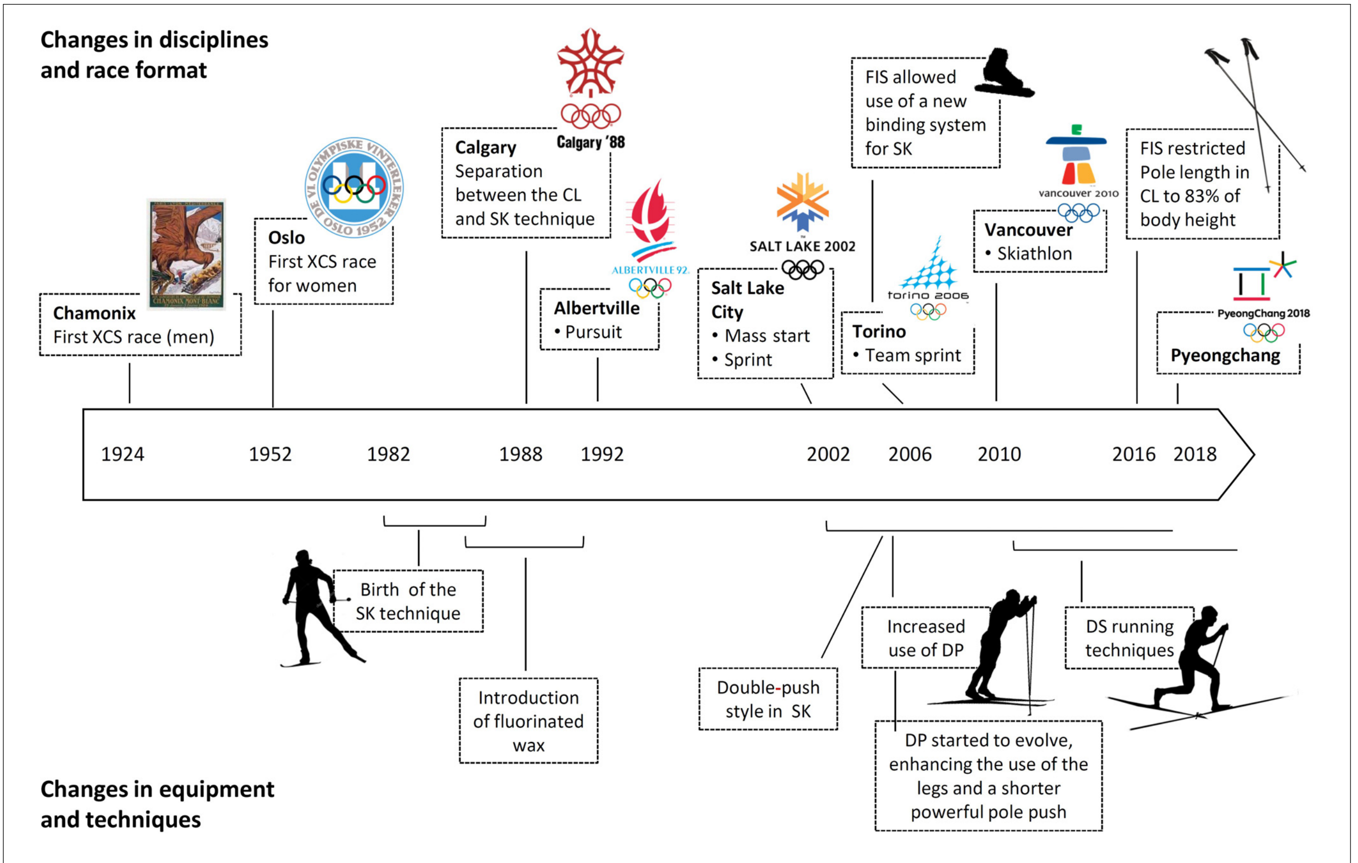


**FIGURE 1 |** Schematic illustration of the major temporal developments in the equipment and biomechanics of Olympic cross-country skiing. Above, the changes in disciplines; and below, the changes in equipment and techniques. XCS, cross-country skiing; FIS, Fédération International de Ski; SK, skating technique; CL, classic technique; DP, double poling; DS, diagonal stride.

(Pellegrini et al., 2014) or energy expended by a skier (Saibene et al., 1989), can be as low as 0.005 on transformed wet snow and as high as 0.035 on cold, fresh snow (Budde and Himes, 2017). During the 50-km freestyle event at the 1992 Winter Olympics, Street and Gregory (1994) observed a significant correlation ($r = -0.73$) between finish time and glide speed. Furthermore, the change in friction due to the texture of a wax or ski base is 0.001–0.010 (Budde and Himes, 2017) and mathematical modeling estimated that lowering the friction coefficient by 0.001 would reduce race time for each kilometer by approximately 2 s (Moxnes et al., 2014).

To improve transmission of the propulsive force of the legs, bindings have been developed to allow more effective control of the skis. Metal bindings were introduced during the first half of the 1900s and a thinner clasp developed in the 1970s. The upper surface of the binding and the boot sole have been shaped to prevent the heel from moving laterally, a necessary constraint for leg pushes when skating.

During the 2005/2006 skiing season, the FIS allowed competitive use of a new binding system based on the clap skate introduced advantageously into ice skating approximately a decade earlier (de Koning et al., 2000; Houdijk et al., 2000). A completely stiff carbon or plastic boot replaces the traditional flexible boot sole and the hinge is beneath, rather than at the tip of the foot, moving the pivot point closer to the ankle joint and shortening the lever arm for more effective leg push-off. In comparison with a conventional system, the skier produces more power that is also more equally distributed over the total push-off, allowing attainment of higher speed over a short distance (Stöggl and Lindinger, 2006). However, this system appears to have no significant effect on skiing economy (Bolger et al., 2016) and probably needs to be adapted further for XC skiing (e.g., with respect to carbon stiffness and pivot point position).

## Poles

Since carbon-fiber alloys and Kevlar wrappings have replaced aluminum as the material for poles, slight changes in design have also occurred. Various ergonomic grips and curved shafts have not proven successful, with apparently little potential for improvement in this connection. A pole shaft with a triangular cross-section introduced recently has a lower moment of inertia during the swing, due to its higher center-of-mass (which allows it to function more effectively as a pendulum), and is also stiffer than the traditional circular shape (Stöggl and Karlöf, 2013) and, therefore, currently most widely used. For application to harder snow, the pole basket has become significantly smaller and is now asymmetric with a diameter of 4–5 cm. Slightly larger ski baskets are sometimes used on new and/or soft snow. To date, no research on the effects of pole basket geometry or size has been reported.

A major challenge with respect to ski poles is achieving sufficient stiffness to apply force efficiently to the track surface. Typical modern racing poles can transmit forces as high as 500–800 N (Swarén et al., 2013b), a value much higher than that normally applied during poling, but which faster skiers can produce at maximal speed (Stöggl and Holmberg, 2011). A major change here involved lengthening classical skiing poles (Nilsson et al., 2003; Hansen and Losnegard, 2010; Stöggl and Karlöf, 2013; Losnegard et al., 2017), which improved oxygen cost (Losnegard et al., 2017; Onasch et al., 2017) and poling mechanics and enhanced peak velocities on both flat and uphill terrain (Stöggl et al., 2010a). However, pole length is limited by recent FIS regulations (see further below).

## DEVELOPMENT OF THE BIOMECHANICS OF THE VARIOUS SKIING TECHNIQUES

Overall, the new race formats, which require more rapid acceleration, have altered the earlier goal of cruising at a high, but economical speed throughout the race (Sandbakk and Holmberg, 2014). Consequently, both classical skiing and skating (Nilsson et al., 2004) have been adapted to produce high peak poling and leg push-off forces (Stöggl and Holmberg, 2011), resulting in some development and/or modification, such as the new "kangaroo" or "modern" DP (Holmberg et al., 2005) and double-push skating or "jump" G3 and G4 skating (Stöggl et al., 2008) techniques.

With DP, higher speed requires both higher peak pole forces and poling force impulse (Holmberg et al., 2005). The time available for propulsion at maximal speed is no more than about 0.21 s (Stöggl et al., 2010a, 2011), approximately 50% of the time available at slower speeds (Lindinger et al., 2009) and comparable to the period of contact between the foot and ground while running (Weyand et al., 2010). The legs play an active role in DP as well (Holmberg et al., 2006); during the recovery phase, the ankles, knees, and hip are extended to raise and push the body's center of mass upward and forward. This process may be so dynamic that the heels and, indeed, sometimes the entire foot are lifted off the ground (Stöggl et al., 2011), making the skier resemble a "kangaroo." The subsequent downward acceleration of the body by gravity transfers force more effectively onto the poles, complementing the propulsion from upper-body work. This converts the potential energy gained during the recovery phase to kinetic energy (Pellegrini et al., 2014). A more pronounced inclination of the body during the initial phase of poling promotes better skiing economy and may allow a more effective subsequent thrust (Zoppirolli et al., 2015). These revolutionary changes led skiers to employ the DP technique more extensively on a variety of inclines over entire race courses (Stöggl and Holmberg, 2016; Welde et al., 2017; Stöggl et al., 2018).

The resulting challenge to the traditional classical style posed by increased DP utilization, the greater requirement for speed during sprint skiing uphill and the desirability of uphill techniques requiring less grip-wax (and, consequently, allowing better glide on other portions of the course) have all contributed to enhanced utilization of the modified, so-called "running DS technique" on steep uphill terrain. Involving little or no gliding, a higher ski position, more vertical forces at ski plant, and flexed knees during the leg swing, this style allows more rapid cycles, thereby producing rapid acceleration and possibly enhancing ski grip on steep and/or challenging terrain (Stöggl and Müller, 2009). During the final of the men's classical sprint in the Pyeongchang Olympic Games, the skiers employed the "kangaroo" DP almost exclusively, except for running DS on uphill sections, sometimes called the "Klæbo" style (**Figure 2**).

Skating skiing developed significantly during the first years after it was introduced. The new sprint event demanded faster acceleration and higher speeds, leading to the so-called "jumped G3 double push" skating, resembling a technique employed by inline speed skaters and involving two pushes with the propulsive leg, rather than one on the inside ski edge (Stöggl et al., 2008). During a 100-m sprint, the double-push technique can produce speeds approximately 3–6.9% faster than those reached with conventional skate skiing, with a lower cycle rate as well (Stöggl et al., 2008). Furthermore, on steep inclines the double-push is as fast as the G2 technique, with a lower cycle rate, and faster than the conventional G3 technique (Stöggl et al., 2010b).

Although the extremely high $VO_{2max}$ of world-class XC skiers has not changed since the 1960s, the new sub-techniques require rapid production of force, emphasizing explosive strength and highly developed motor skills (Stöggl et al., 2008, 2011; Lindinger et al., 2009) and today's elite XC skiers train accordingly (Sandbakk, 2017; Sandbakk and Holmberg, 2017). Better skiers are stronger (Stöggl and Müller, 2009; Stöggl et al., 2010a, 2011), accelerate more rapidly (Wiltmann et al., 2016), possess more lean mass (Stöggl et al., 2010a), and can generate higher peak forces later during the poling phase (Holmberg et al., 2005; Stöggl et al., 2011). Strength has been correlated with starting performance (Wiltmann et al., 2016) and high skiing speed requires extensive involvement of both upper-body and core muscles (Stöggl et al., 2010a; Zoppirolli et al., 2017). Specialists in sprint races are taller and heavier than distance skiers (Losnegard and Hallen, 2014) and competitors in the 50-km classical race in recents Olympic games were heavier (Wood, 2018) than those in the 30-km race in Calgary in 1988 (Norman et al., 1989).

Recently, more focus has also being placed on the downhill sections of a race, where less than 10% of the total racing time is spent, and especially on challenging downhill turns, where faster skiers utilize the accelerating step-turn technique to a greater extent (Sandbakk et al., 2014a,c).


**FIGURE 2 |** Characteristics of the innovative "diagonal running" XC skiing technique by Johannes Høsflot Klæbo (who won three gold medals in Pyeongchang) during the WC sprint in Drammen.

XC skiing competitions for women were introduced at the Oslo Winter Olympic games in 1952, 26 years after the first competitions for men. On the average, women ski 15% more slowly (Sandbakk et al., 2014b) and, in general, compete over shorter racing distances (FIS, 2018), a sex difference unusual for endurance sports. The evolution of female technique has been similar to that of male skiers, although the women's style appears, in general, to be less dynamic. Sex differences in power production by the upper-body are more pronounced than for the legs (Sandbakk et al., 2014b) and, consequently, the corresponding differences in XC skiing performance have become more pronounced as the contribution by the upper body has risen (Hegge et al., 2016). This consideration also influences selection of technique within a race, e.g., on the same intermediate incline, 50% of the men, but less than 10% of the women utilized DP (Stöggl et al., 2018) and, when skating on uphill terrain, women utilize less G3 (more upper-body involvement) than G2.

## TRAINING

Today's XC elite skiers perform more sport-specific training than previously, systematically incorporating roller skiing, as well as training of strength, power, and speed into their routines (Sandbakk, 2017; Sandbakk and Holmberg, 2017). Moreover, ski ergometers for upper-body training (Carlsson et al., 2017) and computerized simulation of specific course profiles on treadmills (Swarén et al., 2013a) are utilized by the best elite skiers.

## ROLE OF FIS REGULATIONS

Developments in XC skiing have been influenced, both directly and indirectly, by FIS regulations. In 1984, to prevent this form of skiing and its sub-techniques from disappearing, new rules required that some races be held with the classical technique. More recently, the choice of DP over other classical sub-techniques, not only by world-class, but also less successful XC skiers, poses a new threat.

Consequently, in 2016/2017, the FIS introduced rules limiting exclusive usage of DP. Pole length can be no longer than 83% of body height; on certain uphill sections (i.e., "technique zones") DP is not allowed; classical racing courses that do not favor exclusive usage of DP are selected (e.g., Oslo, Falun, Val di Fiemme); and track set-up and preparation have been changed (e.g., with a single classical track that follows the "ideal" trajectory and V-boards in curves to prevent extensive usage of lateral skating kicks and/or track changes). Furthermore, stricter surveillance on uphill terrain enforces disqualification for irregular skating strokes.

## FUTURE PERSPECTIVES

Despite these extensive efforts to develop ski equipment, there is still considerable room for improvement. New ski bases (e.g., including flour and shorter carbon chains that will not be banned by future EU regulations designed to reduce fluorinated gases) may enhance performance and prolong effective glide. Moreover, there should be improvement and better standardization of stone grinding, as well as of the microstructure applied manually (e.g., pressure and depth), providing better adaptation to various conditions; improvement of skin-skis for challenging snow conditions; further development of the ski-binding-boot unit (e.g., stiffer units to reduce leakage of mechanical energy and, for the Skiathlon, to make the transition between classic and skating easier, more rapid, and safe) and modifications of the poles to increase their resistance to breaking, without adding weight (especially important for head-to-head races).

Evaluation of the gliding properties of skis, still based on field testing using standard methodology (primarily photocells, test pilots, and athletes), always involves the skier's subjective judgment, but could be made more objective and standardized utilizing sensor technology (Kirby et al., 2018), better management of large datasets, more rapid transfer of test data to practical recommendations (including more powerful statistical analysis), and more effective use of meteorological forecasts. Moreover, technology might also be used to monitor glide/grip and provide better overall evaluation of performance during and following the race.

The significant biomechanical development of skiing techniques over past decades, resulting in higher peak force, power and speed, will continue. Although FIS regulations have apparently reduced exclusive use of DP, thereby preserving the classical technique, future investigations must evaluate which sub-techniques skiers choose in connection with different types of terrain, snow conditions, race formats, and tactical approaches and determine whether these are advantageous in terms of physiological demands and energy expenditure. Such investigations are facilitated substantially by miniaturized GNSS and inertial sensors that can monitor a skier's speed, motion, and technique (Stöggl et al., 2014) continuously and non-invasively during both training and competition.

## ETHICS STATEMENT

This manuscript is based on a review of existing scientific literature and no data involving humans or animals have been acquired directly.

## AUTHOR CONTRIBUTIONS

BP searched the literature, wrote the manuscript, and constructed one of the figures. TS reviewed the first and final versions, added the segments, and constructed one of the figures. H-CH conceived this study, planned the organization of the manuscript, searched the literature, and contributed to the writing.

## REFERENCES


Andersson, E., Supej, M., Sandbakk, Ø., Sperlich, B., Stöggl, T., and Holmberg, H. C. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur. J. Appl. Physiol.* 110, 585–595. doi: 10.1007/s00421-010-1535-2

Bilodeau, B., Roy, B., and Boulay, M. R. (1994). Effect of drafting on heart rate in cross-country skiing. *Med. Sci. Sports Exerc.* 26, 637–641. doi: 10.1249/00005768-199405000-00018

Bolger, C. M., Sandbakk, O., Ettema, G., and Federolf, P. (2016). How hinge positioning in cross-country ski bindings affect exercise efficiency, cycle characteristics and muscle coordination during submaximal roller skiing. *PLoS One* 11:e0153078. doi: 10.1371/journal.pone.0153078

Breitschädel, F. (2012). Variation of nordic classic ski characteristics from Norwegian national team athletes. *Procedia Eng.* 34, 391–396. doi: 10.1016/j.proeng.2012.04.067

Breitschädel, F. (2015). A new approach for the grinding of Nordic skis. *Procedia Eng.* 112, 385–390. doi: 10.1016/j.proeng.2015.07.212

Breitschädel, F., Klein-Paste, A., and Loset, S. (2010). Effects of temperature change on cross-country ski characteristics. *Procedia Eng.* 2, 2913–2918. doi: 10.1016/j.proeng.2010.04.087

Budde, R., and Himes, A. (2017). High-resolution friction measurements of cross-country ski bases on snow. *Sports Eng.* 20, 299–311. doi: 10.1007/s12283-017-0230-5

Carlsson, T., Wedholm, L., Nilsson, J., and Carlsson, M. (2017). The effects of strength training versus ski-ergometer training on double-poling capacity of elite junior cross-country skiers. *Eur. J. Appl. Physiol.* 117, 1523–1532. doi: 10.1007/s00421-017-3621-1

Conconi, F., Borsetto, C., Casoni, I., Droghetti, P., Ferrari, M., Paolini, A. R., et al. (1983). La soglia anaerobica nello sci di fondo. *Scuola Dello Sport* 2:55.

de Koning, J. J., Houdijk, H., De Groot, G., and Bobbert, M. F. (2000). From biomechanical theory to application in top sports: the klapskate story. *J. Biomech.* 33, 1225–1229. doi: 10.1016/S0021-9290(00)00063-4

Ekström, H. (1980). *Biomechanical Research Applied to Skiing*. Linköping: Linköping University.

FIS (2012). *Cross-Country Homologation Manual*. Jacksonville, FL: FIS.

FIS (2018). *The International Ski Competition Rules (ICR) Book II - Cross Country*. Jacksonville, FL: FIS.

Fredrick, E. C., and Street, G. M. (1988). Nordic ski racing: biomedical and technical improvements in cross-country skiing. *Sci. Am.* 258, 20–22.

Hansen, E. A., and Losnegard, T. (2010). Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. *Sports Eng.* 12, 171–178. doi: 10.1007/s12283-010-0042-3

Hegge, A. M., Bucher, E., Ettema, G., Faude, O., Holmberg, H. C., and Sandbakk, Ø. (2016). Gender differences in power production, energetic capacity and efficiency of elite cross-country skiers during whole-body, upper-body, and arm poling. *Eur. J. Appl. Physiol* 116, 291–300. doi: 10.1007/s00421-015-3281-y

Hoffman, M. D., and Clifford, P. S. (1992). Physiological aspects of competitive cross-country skiing. *J. Sport Sci.* 10, 3–27. doi: 10.1080/02640419208729903

Holmberg, H. C. (1996). *Teknik Och Metodik*. Bjästa: CEWE-förlaget.

Holmberg, H. C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scand. J. Med. Sci. Sports* 25(Suppl. 4), 100–109. doi: 10.1111/sms.12601

Holmberg, H. C., Lindinger, S., Stöggl, T., Björklund, G., and Müller, E. (2006). Contribution of the legs to double-poling performance in elite cross-country skiers. *Med. Sci. Sports Exerc.* 38, 1853–1860. doi: 10.1249/01.mss.0000230121.83641.d1

Holmberg, H. C., Lindinger, S., Stöggl, T., Eitzlmair, E., and Müller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sports Exerc.* 37, 807–818. doi: 10.1249/01.MSS.0000162615.47763.C8

Houdijk, H., De Koning, J. J., De Groot, G., Bobbert, M. F., and Van Ingen Schenau, G. J. (2000). Push-off mechanics in speed skating with conventional skates and klapskates. *Med. Sci. Sports Exerc.* 32, 635–641. doi: 10.1097/00005768-200003000-00013

Karlöf, L., Supej, M., and Holmberg, H. C. (2013). "Snow – the performance surface for alpine skiing," in *Routledge Handbook of Ergonomics in Sport and Exercise*, ed. Y. Hong (London: Routledge), 323–334.

Karvonen, J., Kubica, R., Kalli, S., Wilk, B., and Krasicki, S. (1987). Effects of skating and diagonal techniques on skiing load and results in cross-country skiing. *J. Sports Med. Phys. Fitness* 27, 473–477.

Kirby, R., Holmberg, H.-C., and Karlöf, L. (2018). "Understanding ski glide test data – acquisition and interpretation," in *Science and Skiing VII*, ed. M. M. Sport (Aachen: Meyer & Meyer Sport), 365–375.

Kvamme, B., Jakobsen, B., Hetland, S., and Smith, G. (2005). Ski skating technique and physiological responses across slopes and speeds. *Eur. J. Appl. Physiol.* 95, 205–212. doi: 10.1007/s00421-005-1332-5

Lindinger, S. J., Stöggl, T., Müller, E., and Holmberg, H. C. (2009). Control of speed during the double poling technique performed by elite cross-country skiers. *Med. Sci. Sports Exerc.* 41, 210–220. doi: 10.1249/MSS.0b013e318184f436

Losnegard, T., and Hallen, J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *Int. J. Sports Physiol. Perform.* 9, 25–31. doi: 10.1123/ijspp.2013-0066

Losnegard, T., Myklebust, H., Skattebo, Ø., Stadheim, H. K., Sandbakk, Ø., and Hallen, J. (2017). The influence of pole length on performance, O2 cost, and kinematics in double poling. *Int. J. Sports Physiol. Perform.* 12, 211–217. doi: 10.1123/ijspp.2015-0754

Moxnes, J. F., Sandbakk, O., and Hausken, K. (2014). Using the power balance model to simulate cross-country skiing on varying terrain. *Open Access J. Sports Med.* 5, 89–98. doi: 10.2147/OAJSM.S53503

Nilsson, J., Jakobsen, V., Tveit, P., and Eikrehagen, O. (2003). Pole length and ground reaction forces during maximal double poling in skiing. *Sports Biomech.* 2, 227–236. doi: 10.1080/14763140308522820

Nilsson, J., Tveit, P., and Eikrehagen, O. (2004). Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech.* 3, 85–107. doi: 10.1080/14763140408522832

Norman, R., Ounpuu, S., Fraser, M., and Mitchell, R. (1989). Mechanical power output and estimated metabolic rates of Nordic skiers during Olympic competition. *Int. J. Sport Biomech.* 5, 169–184. doi: 10.1123/ijsb.5.2.169

Onasch, F., Killick, A., and Herzog, W. (2017). Is there an optimal pole length for double poling in cross country skiing? *J. Appl. Biomech.* 33, 197–202. doi: 10.1123/jab.2016-0071

Pellegrini, B., Zoppirolli, C., Bortolan, L., Holmberg, H. C., Zamparo, P., and Schena, F. (2013). Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Hum. Mov. Sci.* 32, 1415–1429. doi: 10.1016/j.humov.2013.07.010

Pellegrini, B., Zoppirolli, C., Bortolan, L., Zamparo, P., and Schena, F. (2014). Gait models and mechanical energy in three cross-country skiing techniques. *J. Exp. Biol.* 217, 3910–3918. doi: 10.1242/jeb.106740

Pinchak, A., Hagen, J., Hall, F., and Hancock, D. E. (1987). "Factors affecting performance of cross-country skiers," in *Biomechanics in Sport - a 1987 Update*, eds E. D. Rekow, J. G. Thacker, and A. G. Erdman (New York City, NY: American Society of Mechanical Engineers), 55–60.

Saibene, F., Cortili, G., Roi, G., and Colombini, A. (1989). The energy-cost of level cross-country skiing and the effect of the friction of the ski. *Eur. J. Appl. Physiol. Occup. Phys.* 58, 791–795. doi: 10.1007/BF00637393

Sandbakk, Ø. (2017). The evolution of champion cross-country skier training: from lumberjacks to professional athletes. *Int. J. Sports Physiol. Perform.* 12, 254–259. doi: 10.1123/ijspp.2016-0816

Sandbakk, Ø., Bucher Sandbakk, S., Supej, M., and Holmberg, H. C. (2014a). The velocity and energy profiles of elite cross-country skiers executing downhill turns with different radii. *Int. J. Sports Physiol. Perform.* 9, 41–47. doi: 10.1123/IJSPP.2013-0383

Sandbakk, Ø., Ettema, G., and Holmberg, H. C. (2014b). Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scand. J. Med. Sci. Sports* 24, 28–33. doi: 10.1111/j.1600-0838.2012.01482.x

Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sandbakk, Ø., and Holmberg, H. C. (2017). Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int. J. Sports Physiol. Perform.* 12, 1003–1011. doi: 10.1123/ijspp.2016-0749

Sandbakk, S. B., Supej, M., Sandbakk, Ø., and Holmberg, H. C. (2014c). Downhill turn techniques and associated physical characteristics in cross-country skiers. *Scand. J. Med. Sci. Sports* 24, 708–716. doi: 10.1111/sms.12063

Smith, G. A. (1990). Biomechanics of cross-country skiing. *Sports Med.* 9, 273–285. doi: 10.2165/00007256-199009050-00003

Spring, E., Savolainen, S., Erkkila, J., Hamalainen, T., and Pihkala, P. (1988). Drag area of a cross-country skier. *Int. J. Sport Biomech.* 4, 103–113. doi: 10.1123/ijsb.4.2.103

Stöggl, T., Enqvist, J., Müller, E., and Holmberg, H. C. (2010a). Relationships between body composition, body dimensions, and peak speed in cross-country sprint skiing. *J. Sports Sci.* 28, 161–169. doi: 10.1080/02640410903414160

Stöggl, T., Kampel, W., Muller, E., and Lindinger, S. (2010b). Double-push skating versus V2 and V1 skating on uphill terrain in cross-country skiing. *Med. Sci. Sports Exerc.* 42, 187–196. doi: 10.1249/MSS.0b013e3181ac9748

Stöggl, T., and Holmberg, H. C. (2011). Force interaction and 3D pole movement in double poling. *Scand. J. Med. Sci. Sports* 21, e393–e404. doi: 10.1111/j.1600-0838.2011.01324.x

Stöggl, T., Holst, A., Jonasson, A., Andersson, E., Wunsch, T., Nörstrom, C., et al. (2014). Automatic classification of the sub-techniques (Gears) used in cross-country ski skating employing a mobile phone. *Sensors* 14, 20589–20601. doi: 10.3390/s141120589

Stöggl, T., and Karlöf, L. (2013). Mechanical behaviour of cross-country ski racing poles during double poling. *Sports Biomech.* 12, 365–380. doi: 10.1080/14763141.2013.840855

Stöggl, T., and Lindinger, S. (2006). "Double-push skating and klap-skate in cross country skiing, technical developments for the future?," in *XIV International Symposium on Biomechanics in Sports*, Salzburg.

Stöggl, T., Müller, E., Ainegren, M., and Holmberg, H. C. (2011). General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand. J. Med. Sci. Sports* 21, 791–803. doi: 10.1111/j.1600-0838.2009.01078.x

Stöggl, T., Müller, E., and Lindinger, S. (2008). Biomechanical comparison of the double-push technique and the conventional skate skiing technique in cross-country sprint skiing. *J. Sports Sci.* 26, 1225–1233. doi: 10.1080/02640410802027386

Stöggl, T., Welde, B., Supej, M., Zoppirolli, C., Rolland, C. G., Holmberg, H. C., et al. (2018). Impact of incline, sex and level of performance on kinematics during a distance race in classical cross-country skiing. *J. Sports Sci. Med.* 17, 124–133.

Stöggl, T. L., and Holmberg, H. C. (2016). Double-poling biomechanics of elite cross-country skiers: flat versus uphill terrain. *Med. Sci. Sports Exerc.* 48, 1580–1589. doi: 10.1249/MSS.0000000000000943

Stöggl, T. L., and Müller, E. (2009). Kinematic determinants and physiological response of cross-country skiing at maximal speed. *Med. Sci. Sports Exerc.* 41, 1476–1487. doi: 10.1249/MSS.0b013e31819b0516

Street, G. M., and Gregory, R. W. (1994). Relationship between glide speed and Olympic cross-country ski performance. *J. Appl. Biomech.* 10, 393–399. doi: 10.1123/jab.10.4.393

Swarén, M., Karlöf, L., Holmberg, H. C., and Eriksson, A. (2014). Validation of test setup to evaluate glide performance in skis. *Sports Technol.* 7, 89–97. doi: 10.1080/19346182.2014.968164

Swarén, M., Supej, M., Eriksson, A., and Holmberg, H. C. (2013a). "Treadmill simulation of Olympic cross-country ski tracks," in *Science and Nordic skiing II*, eds A. Hakkarainen, V. Linnamo, and S. Lindinger (Aachen: Meyer and Meyer), 237–242.

Swarén, M., Therell, M., Eriksson, A., and Holmberg, H. C. (2013b). Testing method for objective evaluation of cross-country ski poles. *Sports Eng.* 16, 255–264. doi: 10.1007/s12283-013-0139-6

Welde, B., Stöggl, T. L., Mathisen, G. E., Supej, M., Zoppirolli, C., Winther, A. K., et al. (2017). The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *PLoS One* 12:e0187111. doi: 10.1371/journal.pone.0187111

Weyand, P. G., Sandell, R. F., Prime, D. N., and Bundle, M. W. (2010). The biological limits to running speed are imposed from the ground up. *J. Appl. Physiol.* 108, 950–961. doi: 10.1152/japplphysiol.00947.2009

Wiltmann, V. W., Holmberg, H. C., Pelttari, P., Mikkola, J., Häkkinen, K., Ohtonen, O., et al. (2016). Biomechanical analysis of different starting strategies utilized during cross-country skiing starts. *Eur. J. Sport Sci.* 16, 1111–1120. doi: 10.1080/17461391.2016.1177605

Wood, R (2018). *Anthropometric Measurements of Olympic Cross-Country Skiers*. Available at: https://www.topendsports.com/events/winter/science/x-country-skiing.htm [Accessed 12/4/2018].

Zoppirolli, C., Pellegrini, B., Bortolan, L., and Schena, F. (2015). Energetics and biomechanics of double poling in regional and high-level cross-country skiers. *Eur. J. Appl. Physiol.* 115, 969–979. doi: 10.1007/s00421-014-3078-4

Zoppirolli, C., Pellegrini, B., Modena, R., Savoldelli, A., Bortolan, L., and Schena, F. (2017). Changes in upper and lower body muscle involvement at increasing double poling velocities: an ecological study. *Scand. J. Med. Sci. Sports* 27, 1292–1299. doi: 10.1111/sms.12783

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 20 November 2018
doi: 10.3389/fphys.2018.01631

# Propulsive Power in Cross-Country Skiing: Application and Limitations of a Novel Wearable Sensor-Based Method During Roller Skiing

*Øyvind Gløersen[1,2*], Thomas Losnegard[2], Anders Malthe-Sørenssen[1,3], Dag Kristian Dysthe[1] and Matthias Gilgien[2,4]*

*[1] Condensed Matter Physics, Department of Physics, University of Oslo, Oslo, Norway, [2] Department of Physical Performance, Norwegian School of Sports Sciences, Oslo, Norway, [3] Department of Physics, Center for Computing in Science Education, University of Oslo, Oslo, Norway, [4] Department of Sport Science, Alpine Skiing, Norwegian Ski Federation, Oslo, Norway*

Cross-country skiing is an endurance sport that requires extremely high maximal aerobic power. Due to downhill sections where the athletes can recover, skiers must also have the ability to perform repeated efforts where metabolic power substantially exceeds maximal aerobic power. Since the duration of these supra-aerobic efforts is often in the order of seconds, heart rate, and pulmonary $VO_2$ do not adequately reflect instantaneous metabolic power. Propulsive power ($P_{prop}$) is an alternative parameter that can be used to estimate metabolic power, but the validity of such calculations during cross-country skiing has rarely been addressed. The aim of this study was therefore twofold: to develop a procedure using small non-intrusive sensors attached to the athlete for estimating $P_{prop}$ during roller-skiing and to evaluate its limits; and (2) to utilize this procedure to determine the $P_{prop}$ generated by high-level skiers during a simulated distance race. Eight elite male cross-country skiers simulated a 15 km individual distance race on roller skis using ski skating techniques on a course (13.5 km) similar to World Cup skiing courses. $P_{prop}$ was calculated using a combination of standalone and differential GNSS measurements and inertial measurement units. The method's measurement error was assessed using a Monte Carlo simulation, sampling from the most relevant sources of error. $P_{prop}$ decreased approximately linearly with skiing speed and acceleration, and was approximated by the equation $P_{prop}(v, \dot{v}) = -0.54 \cdot v - 0.71 \cdot \dot{v} + 7.26\ \mathrm{W \cdot kg^{-1}}$. $P_{prop}$ was typically zero for skiing speeds $>9\ \mathrm{m \cdot s^{-1}}$, because the athletes transitioned to the tuck position. Peak $P_{prop}$ was $8.35 \pm 0.63\ \mathrm{W \cdot kg^{-1}}$ and was typically attained during the final lap in the last major ascent, while average $P_{prop}$ throughout the race was $3.35 \pm 0.23\ \mathrm{W \cdot kg^{-1}}$. The measurement error of $P_{prop}$ increased with skiing speed, from $0.09\ \mathrm{W \cdot kg^{-1}}$ at $2.0\ \mathrm{m \cdot s^{-1}}$ to $0.58\ \mathrm{W \cdot kg^{-1}}$ at $9.0\ \mathrm{m \cdot s^{-1}}$. In summary, this study is the first to provide continuous measurements of $P_{prop}$ for distance skiing, as well as the first to quantify the measurement error during roller skiing using the power balance principle. Therefore, these results provide novel insight into the pacing strategies employed by high-level skiers.

**Keywords: work rate, force, energy, GNSS, GPS, validity**



**Edited by:**
*Gregoire P. Millet,
Université de Lausanne, Switzerland*

**Reviewed by:**
*H-C Holmberg,
Mid Sweden University, Sweden
William Bertucci,
Université de Reims
Champagne Ardenne, France*

***Correspondence:**
*Øyvind Gløersen
o.n.gloersen@fys.uio.no*

**Specialty section:**
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:** 29 June 2018*
***Accepted:** 29 October 2018*
***Published:** 20 November 2018*

**Citation:**
*Gløersen Ø, Losnegard T, Malthe-Sørenssen A, Dysthe DK and Gilgien M (2018) Propulsive Power in Cross-Country Skiing: Application and Limitations of a Novel Wearable Sensor-Based Method During Roller Skiing. Front. Physiol. 9:1631. doi: 10.3389/fphys.2018.01631*

# INTRODUCTION

Current cross-country ski races can be categorized into two main events; sprint skiing (<1.8 km) and distance skiing (>10 and 15 km, female and males respectively). Furthermore, races can be held using free technique, where athletes typically choose to use ski skating techniques, or as classic technique races, where skiers are restricted to specific sub-techniques (herringbone, diagonal stride, double poling, kick double poling). Due to these restrictions, the average race speed in free technique events is typically about 10% higher than in classical technique races (Bolger et al., 2015). Regardless of events, the race course regulations specify that courses should contain approximately equal parts of uphill, downhill, and flat terrain, to "test the skier in a technical, tactical and physical manner" (FIS Cross-Country Homologation Manual, June 2017).

Regardless of race distance, cross-country skiing is an endurance sport that demands an exceptionally high aerobic energy turnover, in addition to high movement efficacy. This is underlined by the fact that elite cross-country skiers have among the highest maximal oxygen consumptions of any sports (Sandbakk and Holmberg, 2014; Haugen et al., 2017), typically ranging from 80 to 90 and 70 to 80 $mL \cdot kg^{-1} \cdot min^{-1}$ for world class males and females, respectively (Ingjer, 1991; Losnegard and Hallén, 2014; Sandbakk et al., 2016a). In addition, several studies also indicate substantial anaerobic turnover rates during a race, a phenomenon attributed to the large variations in course inclination. Moreover, skiers typically choose to increase their metabolic power in uphill terrain (Karlsson et al., 2018), often attaining a metabolic power that substantially exceeds their peak aerobic power (estimated at 110–160% of $VO_{2peak}$ Norman and Komi, 1987; Sandbakk et al., 2011; Karlsson et al., 2018). These repeated supra-aerobic efforts vary in duration from seconds to minutes, and incur an oxygen debt that must be recovered in the downhill or flat sections (Sandbakk and Holmberg, 2014; Karlsson et al., 2018). Such transient changes in energetic demand are not well reflected by measurements of pulmonary $VO_2$ or heart rate, because both have a blunted response due to the use of local oxygen stores and anaerobic energy pathways. Hence, both parameters behave as if they passed through a lagged low pass filter and remain high (85–95% of their peak values) throughout the race (Welde et al., 2003; Bolger et al., 2015; Karlsson et al., 2018).

The combination of high and sustained aerobic energy turnover with repeated supra-aerobic efforts distinguishes cross-country skiing from many other endurance racing sports, where the work rate is relatively constant and requires measurement of parameters that reflect the instantaneous energy demands in a competition setting. A frequently used parameter that often corresponds well with instantaneous energy requirement is the propulsive power ($P_{prop}$) generated by the athlete. For some endurance sports, like cycling, $P_{prop}$ can be measured directly, and metabolic energy requirements are approximately linearly related to $P_{prop}$ (Ettema and Lorås, 2009). Hence, if $P_{prop}$ can be linked to metabolic power in skiing (Millet et al., 2003; Sandbakk et al., 2011; Karlsson et al., 2018), in-field measurements of $P_{prop}$ would be useful to further our understanding of the physiological demands experienced by a competitive skier. Therefore, several studies have attempted to calculate $P_{prop}$ during cross-country skiing, based either on position measurements (Sandbakk et al., 2011; Swarén and Eriksson, 2017), or simulation of skiing performance (Moxnes and Hausken, 2008; Carlsson et al., 2011; Moxnes et al., 2013, 2014; Sundström et al., 2013). These studies all use the principle of power balance, as outlined by van Ingen Schenau and Cavanagh (1990). However, no studies are available where $P_{prop}$ has been measured continuously throughout a cross-country ski race with a duration longer than sprint skiing. Furthermore, no previous studies have critically evaluated the accuracy achieved when applying the power balance principle to cross-country skiing. The aims of this study were (1) to develop a procedure for estimating the propulsive power generated during roller-skiing using small non-intrusive sensors (GNSS and IMUs) attached to the athlete and evaluate its limitations; and (2) to utilize this procedure to determine the propulsive power generated by high-level skiers during a simulated distance race.

## Theoretical Background

As stated by van Ingen Schenau and Cavanagh (1990), the $P_{prop}$ is equal to the rate of change in mechanical energy ($E_{mech}$) of the system and the work done on the environment ($W_{env}$). In cross-country skiing $P_{prop}$ is customarily estimated by modeling the skier and his/her equipment as a point mass (Moxnes and Hausken, 2008; Carlsson et al., 2011; Moxnes et al., 2013, 2014; Sundström et al., 2013; Swarén and Eriksson, 2017). Under this assumption, the mechanical energy is the sum of translational kinetic energy and the gravitational potential energy. Work done on the environment is primarily due to ski/snow-friction forces (or rolling resistance, denoted $\mathbf{F}_f$) and the aerodynamic drag force ($\mathbf{F}_d$). This is summarized in Equation 1:

$$\begin{aligned} P_{prop} &= \dot{E}_{mech} + \dot{W}_{env} \\ &= \underbrace{\left(m\dot{\mathbf{v}} - \mathbf{F}_g - \mathbf{F}_d - \mathbf{F}_f\right) \cdot \mathbf{v}.}_{\text{Point mass assumption}} \end{aligned} \tag{1}$$

In Equation 1 $m$ refers to the total mass of the system (the sum of body mass and equipment), $\mathbf{v}$ is the velocity of the center of mass (COM), $\dot{\mathbf{v}}$ is the COM acceleration, and $\mathbf{F}_g$ is the gravitational force. Furthermore, the magnitude of the propulsive force ($F_{prop}$), i.e., the force in the skiing direction that is not due to gravity or frictional forces (air drag, ski/snow-friction or rolling friction) is calculated using $F_{prop} = P_{prop} \cdot |v|^{-1}$ (Carlsson et al., 2011).

For skiing and roller skiing applications $\mathbf{F}_f$ has commonly been modeled using the Amonton-Coulomb equations (Carlsson et al., 2011; Moxnes et al., 2013, 2014; Sundström et al., 2013; Swarén and Eriksson, 2017). This friction model is attractive because of its simplicity, but it is unable to capture complex ski-snow interactions (Bowden and Hughes, 1939; Buhl et al., 2001; Theile et al., 2009), and $\mathbf{F}_f$ may change considerably over the course due to changing snow conditions. This challenge can be partially overcome using roller skis, which have a more constant coefficient of rolling resistance, except during the warm-up period (Ainegren et al., 2008). Another limitation is that during turns or when employing ski-skating techniques the skis (or roller skis) are actively pushed in the mediolateral direction, which causes shear forces. One study has investigated how the rolling resistance of a roller ski was affected by shear forces occurring during the ski push-off (Sandbakk et al., 2012). They concluded that the ratio of the rolling resistance force to the vector sum of shear and compression forces varied by <2% for ski angles up to 45°. This finding suggests that when evaluating rolling resistance during roller ski skating, shear forces (caused by ski push-off or centripetal forces during a turn) can be added to the normal force, at least for the wheel type assessed by Sandbakk et al. (2012).

Work done against the aerodynamic drag force has conventionally been modeled using the drag equation from fluid dynamics (Carlsson et al., 2011; Moxnes et al., 2013, 2014; Sundström et al., 2013; Swarén and Eriksson, 2017):

$$\mathbf{F}_d = -\tfrac{1}{2}\rho v_f^2 \cdot AC_D\,(\mathrm{Re})\cdot \hat{\mathbf{v}}_\mathbf{f}. \quad (2)$$

In Equation 2, ρ denotes the air density, $\boldsymbol{v}_\mathrm{f}$ denotes the velocity relative to the air, and $\hat{\boldsymbol{v}}_\mathrm{f}$ the unit vector along $\boldsymbol{v}_\mathrm{f}$. The drag area ($AC_D$) is the product of the frontal area $A$ of the athlete and equipment and the drag coefficient ($C_D$), which depends on the shape and surface material properties of the object in the air flow. $C_D$ also depends upon the Reynolds number:

$$\mathrm{Re} = \frac{\rho L v_f}{\mu}. \quad (3)$$

In Equation 3, $\rho$ denotes the fluid's density, $L$ is the characteristic length of the object, and $\mu$ is the dynamic viscosity. $C_\mathrm{D}$ is relatively constant when the flow is turbulent, except for a sharp drop when the boundary layer transitions from semi-turbulent to fully turbulent flow, resulting in a narrower wake behind the object (Spurk and Aksel, 2008). This phenomenon usually occurs at Re around $2 \times 10^5$ and is well studied for simple blunt bodies (Achenbach, 1968; Spurk and Aksel, 2008). The drop in $C_\mathrm{D}$ has also been shown to exist for athletes while roller skiing (Spring et al., 1988) and during wind tunnel simulations of ice skating (van Ingen Schenau et al., 1982), where the transitions occurred at about 5 and 10 $\mathrm{m{\cdot}s^{-1}}$, respectively. The magnitude of the change in $C_\mathrm{D}$ varies considerably between different studies. Data from Achenbach (1968) and van Ingen Schenau et al. (1982) showed that $C_\mathrm{D}$ was reduced to about 30–40% of its quasi-stable value for Re $< 10^5$, while data from Spring et al. (1988) implied a decrease to about 10%. There are two more challenges when estimating $\mathbf{F}_\mathrm{d}$ from Equation 2: (i) wind velocity must be known in order to find $v_\mathrm{f}$; and (ii) the drag area depends on the skier's posture and (indirectly) on skiing speed, through the Reynolds number. Previous studies have estimated $AC_\mathrm{D}$ as constant (Swarén and Eriksson, 2017), or as a step or smooth function of skiing speed using allometric scaling based on body mass (Sundström et al., 2013; Moxnes et al., 2014), and only one study has investigated the effect of non-zero wind velocity (Moxnes et al., 2014). These simplifications are often necessary because direct measurement of instantaneous wind field and drag area are challenging or impossible in the field. Nonetheless, the error arising from these approximations has rarely been addressed.

# MATERIALS AND METHODS

## Participants and Study Design

The data presented in this study were collected over three test days on the roller skiing course at Holmenkollen, Oslo, Norway. The topography of the course is similar to race courses used in competitive cross-country skiing on snow (height difference 51 m, maximum climb 32 m, total climb 166 m). Eight skiers (seven cross-country skiers; FIS point range of 13–117, and one biathlete) volunteered for the study and gave their written consent to participate. The study was approved by the ethics committee at the Norwegian School of Sport Sciences and the Norwegian Centre for Research Data, and was conducted according to the Declaration of Helsinki.

The participants were asked to complete a test race consisting of three laps of a 4.5 km course in the shortest time possible. The test race was arranged as a time trial and the participants were instructed to the use skating techniques. All participants used the same model of roller skis (Swenor Skate Long, wheel type 2), and wore tight-fitting clothing. Each participant was equipped with two identical position tracking devices (Catapult Optimeye S5, mass 67 g) consisting of a 10 Hz standalone GNSS-module and a 9-axis inertial measurement unit (accelerometer, gyroscope and magnetic field measurements). One of the receivers, carried in a tight-fitting vest, was positioned at approximately the level of the third thoracic vertebra, while the other was taped laterally on the thigh approximately 10 cm inferior to the trochanter (**Figure 1**). Both units were attached so that the inertial sensors' local coordinate systems (*xyz*) were approximately aligned with the *x*-axis directed the mediolaterally to the right (in the skiing direction) and the *y*-axis in the anterior direction. Prior to the test race the weight of the athletes and equipment (including ski boots, roller skis, ski poles and helmet) was recorded, and the participants performed calibration measurements for the drag area model, as described in section Frontal Area. After completing these measurements, the athletes warmed up for approximately 30 min before the race started.

To allow more accurate determination of vertical position, the GNSS positions from the receivers carried by the athletes were mapped onto a common trajectory that was determined from kinematic position tracking using a more accurate differential GNSS (receiver: Alpha-G3T, antenna: GrAnt-G3T, Javad, USA). These measurements had an expected accuracy <5 cm (Gilgien et al., 2014b) when double difference ambiguities were fixed. The ambiguities could not be solved for five short sections of the course, resulting in a substantially reduced accuracy in these sections (expected errors >1 m Gilgien et al., 2014b). These sections are clearly marked in the results.

## Environmental Conditions

Air temperature and pressure were recorded during the race for each day of testing. Wind velocities (measured 10 m above the ground) were retrieved hourly from weather stations located approximately 2.3 km (Tryvann) and 3.7 km (Blindern) from the roller skiing course (www.met.eklima.no, Meteorological Institute of Norway, Oslo, Norway). The wind velocities were averaged and corrected to 1 m height above the ground using

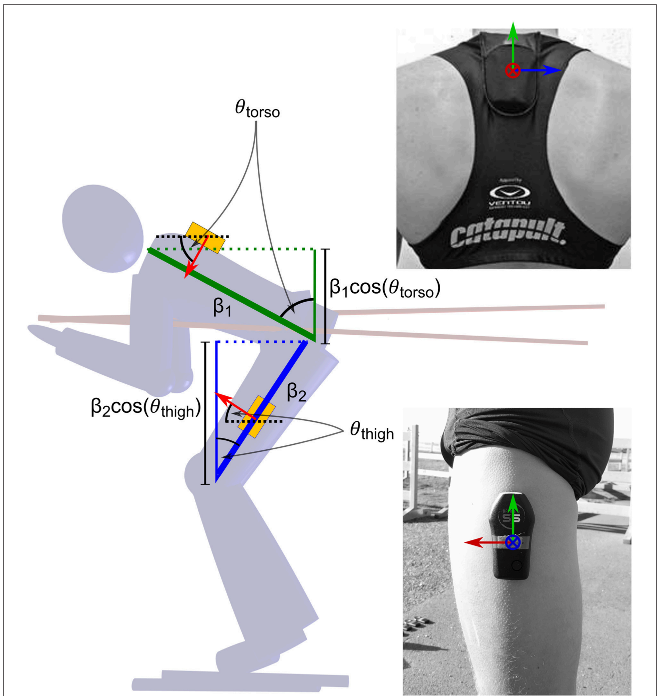


**FIGURE 1 |** Positioning of the two IMUs on the athletes' body and motivation for the frontal area model described in Equation 5. One IMU was positioned approximately at the level of the third thoracic vertebra, the other was taped laterally on the thigh approximately 10 cm inferior to the trochanter. The axes were aligned with the x-axis (blue) in the mediolateral direction and the y-axis (red) in the anterior direction. The z-axis (green) was aligned with gravity when the athletes were in a standing posture, as described in the text. The frontal areas of the torso and thighs scale approximately with the cosine of the pitch angles $\theta_k = \text{atan}(a_{y,k}/a_{z,k})$, where $a_{y,k}$ and $a_{z,k}$ are the smoothed accelerometer outputs along the y and z-axis respectively. *k* represents the thigh or torso location.

the log wind profile relationship (Oke, 1978) with a roughness length of 0.1 m, resulting in wind speeds exactly half of the data measured 10 m above the ground.

## Data Processing and Filtering

The GNSS positions and inertial sensor data from the receivers mounted on the athletes were exported using Catapult Sprint software version 5.1.7 at sampling frequencies of 10 and 100 Hz, respectively. Differential GNSS positions for the reference trajectory were calculated using the kinematic algorithm of the geodetic post-processing software Justin (Javad, San Jose, CA, USA). All other analyses were performed using Matlab R2017a (MathWorks, Natick, MA, USA).

The reference trajectory was resampled to equidistantly (1 meter) spaced points, and then filtered using smoothing splines weighted by their fixed/float status (Skaloud and Limpach, 2003) using a smoothing parameter of $p = 0.02$. The GNSS positions obtained from the receivers mounted on the athletes were filtered with a second order bidirectional Butterworth low pass filter with a cutoff frequency of 0.3 Hz, which removed the high frequency components that could not be attributed to the center of mass trajectory due to the receiver's antenna location. The cutoff-frequency was chosen based on a frequency-analysis of motion capture data from skiing using the V1 and V2 techniques. Only the GNSS positions from the receiver on the torso were used for skier position calculation. Vertical position ($z$) was obtained by mapping the horizontal plane position from the standalone GNSS receiver carried by the athlete onto the 3D reference trajectory. This was achieved by minimizing horizontal plane Euclidean distance from the position measurement of the standalone GNSS receiver to any point on the reference trajectory. After filtering and projection of the standalone GNSS positions onto the reference trajectory the trajectories were down-sampled to a frequency of 1 Hz prior to work rate calculations, to limit the computational load. Finally, external work rate was filtered using a 5 second bidirectional moving average filter.

## Mechanical Energy

For calculation of mechanical energy, a point mass $m$ equal to the combined mass of the athlete and his equipment was utilized. With this approach the gravitational potential energy is $mgz$, where $g = 9.81\text{m}\cdot\text{s}^{-2}$ is the acceleration due to gravity and $z$ the vertical position. The kinematic energy is $0.5\text{m}|\mathbf{v}|^2$, where $\mathbf{v}$ is the skiing velocity. The skiing velocity was determined by differentiating the horizontal plane positions from the standalone GNSS receiver carried by the athlete and the vertical component of velocity was calculated using the using the mapped vertical position. Velocity was calculated using a five-point finite difference algorithm (Gilat and Subramaniam, 2008).

## Rolling Resistance

Rolling resistance was measured individually for each athlete using a towing test on the roller skiing treadmill at the Norwegian School of Sport Sciences, as described by Hoffman et al. (1990). The coefficient of rolling resistance ($C_{rr}$) was 0.0225 ± 0.0009 (mean ± standard deviation). The rolling resistance of one of the pairs of roller skis on asphalt (determined by a towing test) was the same as on the treadmill surface, in agreement with the findings of Myklebust (2016), and the former were therefore used in the calculations of work against rolling resistance. The roller skis were assumed to move the same distance as the GNSS antenna, and centripetal forces ($\mathbf{F}_c$, caused by the course's curvature) were added to the normal force opposing gravity ($\mathbf{N}_g$), following the findings of Sandbakk et al. (2012). Hence, the work rate against rolling resistance was estimated using the following equation:

$$\dot{W}_f = C_{rr}\cdot \left|\mathbf{N}_g+\mathbf{F}_c\right| \cdot v. \quad (4)$$

In Equation 4, $\mathbf{N}_g$ was defined as minus the component gravity perpendicular to the course's normal vector, and the course was assumed to be level in the mediolateral direction. Centripetal force was calculated using $\mathbf{F}_c = m|\mathbf{v}|^2\cdot\mathbf{K}$, where $\mathbf{K}=-\mathbf{v}\times(\mathbf{v}\times\dot{\mathbf{v}})/v^4$ is the track curvature vector (Dooner, 2012).

## Air Drag Model

Air drag was determined from Equation 2, with the drag area as defined in the next two paragraphs. Air density $\rho_{\text{air}}$ =

$p \cdot R_{\text{specific}}^{-1} T^{-1}$ was calculated from measured air pressure using the ideal gas law with $R_{\text{specific}} = 287.058$ J·kg$^{-1}$·K$^{-1}$, and $p$ and $T$ equal to the measured air pressure and temperature, respectively. Dynamic viscosity ($\mu_{\text{air}}$) was calculated as a function of air temperature using Sutherland's formula, as described by Canuto et al. (2007). Wind velocity was defined as described in section Statistics and was subtracted from the skiing velocity vector. Finally, the power dissipated through air drag was the dot product $\mathbf{F}_{\text{d}} \cdot \mathbf{v}$.

### Frontal Area

The skiers' frontal area $A$ was approximated continuously during the entire trial using the accelerometer data provided by the sensors mounted on the torso and thigh. First, the accelerometers' coordinate frames were rotated so that the z-axis was parallel to the gravity vector during a static standing pose (**Figure 2A**, pose 1), and the x-axis was directed mediolaterally. This was achieved by performing two successive rotations, the first canceling lateral tilt and the second canceling forward tilt (Myklebust et al., 2015). Second, the signals were filtered with a 2 second bidirectional moving average filter. Third, the smoothed pitch angles $\theta_{\text{thigh}}$ and $\theta_{\text{torso}}$ were calculated using $\tan(\theta) = a_y/a_z$, where $a_y$ and $a_z$ denote the smoothed accelerometer outputs (in a standing posture) along the forward and vertical directions. With this definition, the pitch angle represents a rotation about the IMU's $x$-axis that will align the $y$-axis with the horizontal plane. As shown in **Figure 1**, the frontal areas of the torso or thigh segments will scale approximately with the cosine of this angle. Therefore, $\theta_{\text{thigh}}$ and $\theta_{\text{torso}}$ were used to predict the frontal area $A$ of the athlete using the following equation:

$$\frac{A - A_{\text{equip}}}{A_{0,j}} = \beta_0 + \beta_1 \cos(\theta_{torso}) + \beta_2 \cos\left(\theta_{thigh}\right). \tag{5}$$

Here $A_{0,j}$ denotes the frontal area of athlete $j$ while standing upright, as shown in **Figure 2A**, and $A_{\text{equip}} = 0.045$ m$^2$ was a constant that was added to represent the average frontal areas of the roller skis and ski poles. The three parameters $\beta_{0,1,2}$ were determined using multiple linear regression with $\cos(\theta_{\text{thigh},(i,j)})$ and $\cos(\theta_{\text{torso},(i,j)})$ as predictors, and 56 frontal areas $A_{(i,j)}$ (i.e., seven frontal areas per participant) with different postures as the dependent variable (**Figures 2A,C**). The 56 frontal areas were calculated from digital images (resolution 3,264 × 4,928 pixels) taken of the skiers prior to the trial, and the pixel size was determined using an object of known length placed directly lateral to the athlete. The characteristic length $L_j$ in Equation 3 was defined as the width of athlete $j$ in the pelvis/abdomen region and was determined from the first of the 7 images (**Figure 2A**).

### Determination of the Frontal Area by Allometric Scaling

We also tested a drag area model that simplifies data collection and analysis, because it does not require measurements of frontal areas or measurements from inertial sensors. First, the estimated frontal areas determined from Equation 5 were normalized by $m^{2/3}$, where $m$ was body mass and 2/3 is the allometric scaling exponent (Günther, 1975; Bergh, 1987). Second, the normalized frontal areas were assumed to be a sigmoid function of skiing speed $v$, as previously assumed by Moxnes et al. (2014) and Sundström et al. (2013). To model this sigmoid shape, we defined a logistic function:

$$\frac{A(v)}{m^{2/3}} = \gamma_1 - \frac{\gamma_2}{1+e^{-\left(\frac{v}{\gamma_4} - \gamma_3\right)}}. \tag{6}$$

The four-parameter vector $\boldsymbol{\gamma}$ was determined by minimizing the sum of the squared residuals from the normalized estimates of drag area ($A \cdot m^{-2/3}$) determined from Equation 5 using the Levenberg-Marquardt algorithm. Hence, once $\boldsymbol{\gamma}$ was established, the only necessary input was body mass and skiing speed.

### Drag Coefficient

The drag coefficient $C_{\text{D}}$ was modeled as a function of the Reynolds number (Re) using a logistic function fitted to the data from Achenbach (1968). Specifically, the four-parameter vector $\boldsymbol{\alpha}$ was determined by minimizing the sum of the squared residuals between measurements and the model in Equation 7 (below) using the Levenberg-Marquardt algorithm (implemented in Matlab's Statistics and Machine Learning toolbox):

$$C_D{}'(\text{Re}) = \alpha_1 - \frac{\alpha_2}{1+e^{-\left(\frac{\text{Re}}{\alpha_4} - \alpha_3\right)}}. \tag{7}$$

Only measurements with Reynolds numbers in the range $[4 \times 10^4, 5 \times 10^5]$, which corresponds to conditions relevant to cross-country skiing (speeds in the range 2–25 m·s$^{-1}$, assuming $\mu \cdot \rho^{-1} = 1.5 \times 10^{-5}$ m$^2$·s$^{-1}$ and L = 0.30 m) were used for the fitting procedure (**Figure 2C**). In the second step, the model in Equation 7 was scaled to match the mean drag coefficients of speed skaters measured at 12 m·s$^{-1}$ by van Ingen Schenau et al. (1982). This was done by calculating the Reynolds number ($\text{Re}_{\text{Schenau}}$) for the conditions described in van Ingen Schenau et al. (1982), and then applying the following equation:

$$C_D(\text{Re}) = \frac{C_{D,\text{Schenau}}}{C_D{}'(\text{Re}_{\text{Schenau}})} C_D'(\text{Re}). \tag{8}$$

## Tuck Position

When in the tucked position, skiers do not generate any significant propulsive force. As all cross-country skiing techniques (except the tucked position) require substantial rotation of both the thorax and thigh segments, measurements of the segments' angular rates were used to determine when the athletes were in the tucked position. Specifically, the squared magnitude of the angular velocity vector from the gyroscopes was used as a decision criterion. These signals were filtered with a 2 second bidirectional moving average filter, and athletes were defined to be in the tuck position when both devices (on thigh and thorax) showed values smaller than 5,000$^{\circ 2}$·s$^{-2}$. This threshold was determined by inspecting the signal distributions (**Figure 3**). $P_{\text{prop}}$ was set to zero when the athletes were in the tucked position.

## Statistics

Confidence intervals for the calculated work rates were determined using a Monte Carlo approach. The effect of changing wind velocity and errors in drag area and rolling

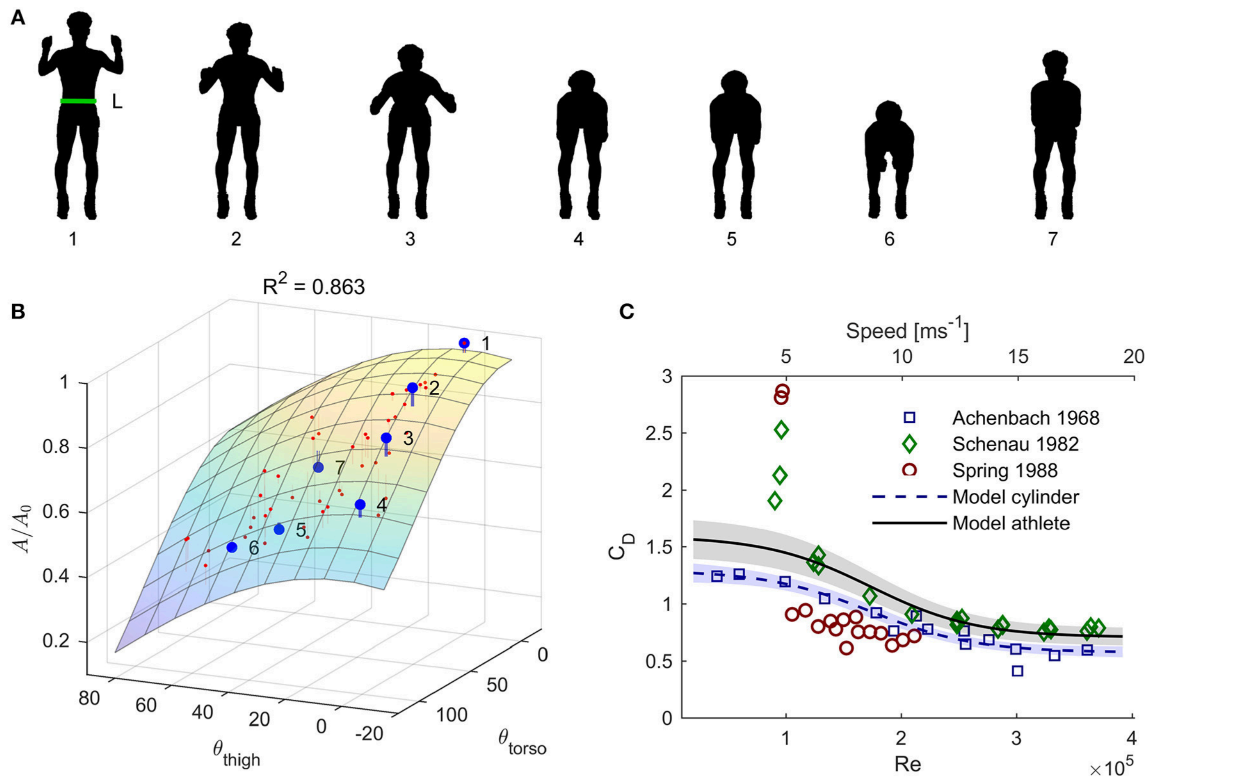


**FIGURE 2 | (A)** Postures used to calculate frontal area. The first pose for each athlete was used to calculate the characteristic length $L$ (Equation 3), which was defined as the width at the height of the pose's center of mass (green line). **(B)** Model for the frontal area $A$ based on the postures in **(A)** and Equation 5. The data points are enumerated to match the postures in **(A)**, and show the measurements from one subject. Red dots indicate measurements from all other subjects. **(C)** Model (Equations 7, 8) for the drag coefficient of a skier as a function of the Reynolds number (solid black line). Blue squares: data from Achenbach (1968); Green diamonds: data from van Ingen Schenau et al. (1982); Red circles: data from Spring et al. (1988); Dashed blue line: model fitted to Achenbach's measurements. The upper and lower x-axis were related by Equation 3 using atmospheric conditions as specified in van Ingen Schenau et al. (1982) and $L = 0.3$ m. Shaded areas indicate the models' standard deviations, and were obtained using Monte Carlo simulations ($N = 5{,}000$) sampled from the distributions specified in the statistics section.

resistance were modeled by sampling from distributions as described in this section. 2,500 Monte Carlo samples were used for each of the participants.

Wind speed was assumed to be Rayleigh distributed (Dorvlo, 2002) with an expectation value equal to the hourly average wind speed after correction for height above ground, and averaged over the two measurement stations. Wind direction was assumed to be normally distributed with an expectation value equal to the hourly average and a standard deviation of 25 degrees.

Errors in frontal area estimates (Equation 5) were assumed to be $\sim N(0, \sigma^2_{\text{resid}})$, $\sigma_{\text{resid}}$ being the standard deviation of the model residuals. The distribution of the coefficients $\boldsymbol{\alpha}$ in Equation 7 was assumed to be $\sim N(\boldsymbol{\alpha}_{\text{opt}}, \boldsymbol{\sigma}^2_{\text{opt}})$, where $\boldsymbol{\alpha}_{\text{opt}}$ and $\boldsymbol{\sigma}_{\text{opt}}$ were the coefficient estimates and covariance matrix obtained from the optimization procedure. $C_{D,\text{Schenau}}$ was defined to be $\sim N(0.872, 0.079^2)$, which corresponds to the mean and standard deviation of the findings in Table 1 of van Ingen Schenau et al. (1982).

The coefficient of rolling resistance was assumed to be normally distributed with an expectation value equal to the measured values from the treadmill towing test and standard deviation $2.3 \times 10^{-3}$, which was the standard error of the measurements from the towing test on asphalt. Asphalt values were used for the standard deviation, since these were assumed to better represent the variability of field conditions.

The method's accuracy was defined as the pooled standard deviation of $P_{\text{prop}}$ and $F_{\text{prop}}$ obtained from the Monte Carlo simulation. The method's sensitivity was assessed by comparing inter-athlete and intra-athlete differences in $F_{\text{prop}}$ to the method's accuracy. This was achieved by calculating the empirical cumulative distribution function of the inter-athlete or intra-athlete standard deviation (i.e., the lap-to-lap variability) of $F_{\text{prop}}$. The method was considered suitable to discriminate differences in $F_{\text{prop}}$ if the standard deviation was greater than the measurement accuracy for >90% of the measurements. To test the method's sensitivity in optimal conditions, the Monte Carlo simulation was run again with zero wind speed. All other parameters were kept constant.

# RESULTS

## Physiological Aspects

A graphical presentation of $P_{\text{prop}}$ as a function of distance traveled is provided in **Figure 4**, which clearly shows that there were substantial variations in $P_{\text{prop}}$ throughout the test race.

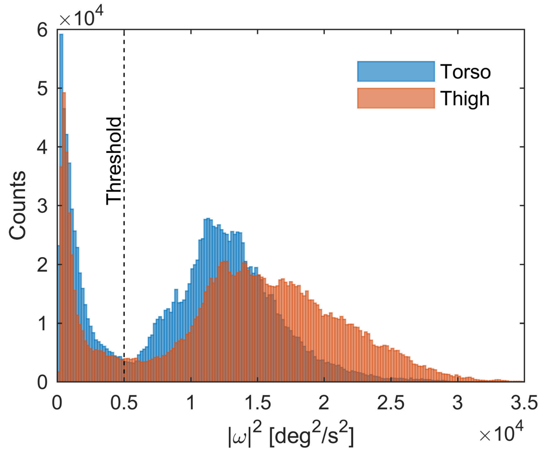


**FIGURE 3 |** Histogram of the squared magnitude of gyroscope measurements (angular velocity) during skiing for all athletes. The distinct distribution minimum at about 5,000$^{\circ 2}$s$^{-2}$ indicates the transition from the tucked position, where movements of both torso and thigh are small, to skiing techniques that generate propulsion. In the current study, the athletes were assumed to be in the tucked position when $|\omega|^2$ of both torso and thigh were <5,000$^{\circ 2}$·s$^{-2}$.

**TABLE 1 |** Results for the regression parameters (**β**) for frontal area calculation (Equation 5), parameters (**α**) for the drag coefficient model (Equation 7), and parameters (**γ**) for prediction of frontal areas using body mass and skiing speed (Equation 6).

| | α | | γ | | β | |
|---|---|---|---|---|---|---|
| **Index** | **Coeff** | **95% CI** | **Coeff** | **95% CI** | **Coeff** | **95% CI** |
| 0 | 1.29 | [1.07, 1.52] | 0.0289 | [0.0289, 0.0290] | 0.27 | [0.21, 0.33] |
| 1 | 0.72 | [0.45, 0.99] | 0.0094 | [0.0093, 0.0096] | 0.32 | [0.29, 0.35] |
| 2 | 4.55·10$^4$ | [0.93, 8.17] ·10$^4$ | 12.2 | [11.6, 12.7] | 0.38 | [0.31, 0.45] |
| 3 | 3.82 | [0.09, 7.54] | 0.76 | [0.72, 0.79] | – | – |

$P_{prop}$ was 3.35 ± 0.23 W·kg$^{-1}$ when averaged over the race duration, and 4.18 ± 0.41 W·kg$^{-1}$ when omitting measurements where the athletes were in the tucked position (termed active propulsive power, Swarén and Eriksson (2017)). Peak $P_{prop}$ was typically attained on the last major ascent during the final lap (at 3,600–3,730 m from the start of the lap in **Figure 4**). The average of the athletes' peak $P_{prop}$ was 8.35 ± 0.63 W·kg$^{-1}$. When comparing $P_{prop}$ at the same positions along the course, lap-to-lap differences were small, except for a distinct starting spurt for the initial 200 meters of the first lap (**Figures 4B,C**). $P_{prop}$ was also higher in the last two uphills of the third lap (3,600–3,730 and 4,120–4,170 m) compared to the first lap, indicating an end spurt (**Figure 4C**).

Overall, $P_{prop}$ showed an approximately linear relationship with skiing speed (**Figure 5A**), except for speeds where the skiers were in the tucked position. The transition into the tucked position occurred at skiing speeds ∼9 m·s$^{-1}$ (**Figure 6**). Furthermore, $P_{prop}$ was dependent on the acceleration along the skiing direction; a positive acceleration correlated with smaller $P_{prop}$, and negative accelerations with higher $P_{prop}$. This is consistent with observations from **Figure 4A**, where $P_{prop}$ appeared to decline slightly from its initial values in the longer ascents (450–600, 1,200–1,330, 2,030–2,450 m from the start, **Figure 4D**). This implies that $P_{prop}$ was higher when the skier decelerated at the start of a climb, and lower when accelerating over the top of a climb. A multiple least squares regression fit on $P_{prop}$ using skiing speed and acceleration as predictors had the coefficients −0.54 N·kg$^{-1}$, −0.71 N·s·kg$^{-1}$ and intercept 7.26 W·kg$^{-1}$ (**Figure 5A**), and a coefficient of determination $R^2$ = 0.403. This indicates that a substantial fraction of the variability in $P_{prop}$ could not be explained by skiing speed and acceleration alone. In **Figure 5B** skiing speed is plotted against the course inclination. The line predicting steady state skiing speed based on the least squares fit $P_{prop}(v,\dot{v})$ was also added to the figure (see figure legend for details). The data points where the skier was close to a steady state skiing speed (i.e., $|\dot{v}|$ is small) fell along the line suggested by the least squares fit. Data points far from the line suggested by the least squares fit was typically from periods with large positive acceleration (points below the line, colored red in **Figure 5B**) or negative acceleration (points above the line, colored blue in **Figure 5B**).

## Methodological Aspects

In **Figure 6**, Frontal areas (normalized to body mass) are plotted vs. skiing speed. The frontal area changed from the typical standing posture for $v$ < 8 m·s$^{-1}$ to a tucked-position for $v$ > 10 m·s$^{-1}$ (**Figure 6A**). Due to the dependency of $C_D$ on the Reynolds number, the behavior was more complex for the drag area, which continuously decreased almost throughout the range of skiing speeds observed during the race (**Figure 6B**).

The Monte Carlo simulation showed that errors in $F_{prop}$ were on average 5.1 · 10$^{-2}$ N·kg$^{-1}$ and increased slowly with skiing speed (**Figure 7A**). The least squares regression line of $F_{prop}$ with respect to skiing speed had a slope of 2.8 ·10$^{-3}$ N·s·m$^{-1}$·kg$^{-1}$ and intercept 3.9 · 10$^{-2}$ N·kg$^{-1}$. Therefore, the error in $P_{prop}$ increased curvilinearly with skiing speed, approximately following the expression $2.8\cdot10^{-3}\cdot v^2 + 3.9\cdot 10^{-2}\cdot v$ (**Figure 7B**). Hence, estimates of $P_{prop}$ were most accurate at low skiing speeds (∼0.09 W·kg$^{-1}$ at 2.0 m·s$^{-1}$, close to the lowest measured speeds) and less accurate at high speeds (∼0.58 W·kg$^{-1}$ at 9.0 m·s$^{-1}$ close to the speed when most athletes transitioned to the tucked position).

The method's applicability to discriminate between instantaneous inter-athlete and intra-athlete differences in $F_{prop}$ is shown in **Figure 8**. The results show that with the test conditions in the current study, neither inter-athlete or intra-athlete differences could be reliably detected. This conclusion holds true even in zero-wind conditions, where 29.9% (intra-athlete) and 79.9% (inter-athlete) of the measurements contained differences that exceeded the measurement accuracy.

For all results reported above, $P_{prop}$ was calculated using vertical position measurements obtained by mapping the positions onto a reference trajectory of dGNSS measurements and using frontal area estimates from two accelerometers positioned at the thorax and thigh. Omitting the mapping procedure (by using the vertical position measurements of the standalone receivers carried by the athletes) yielded a root mean

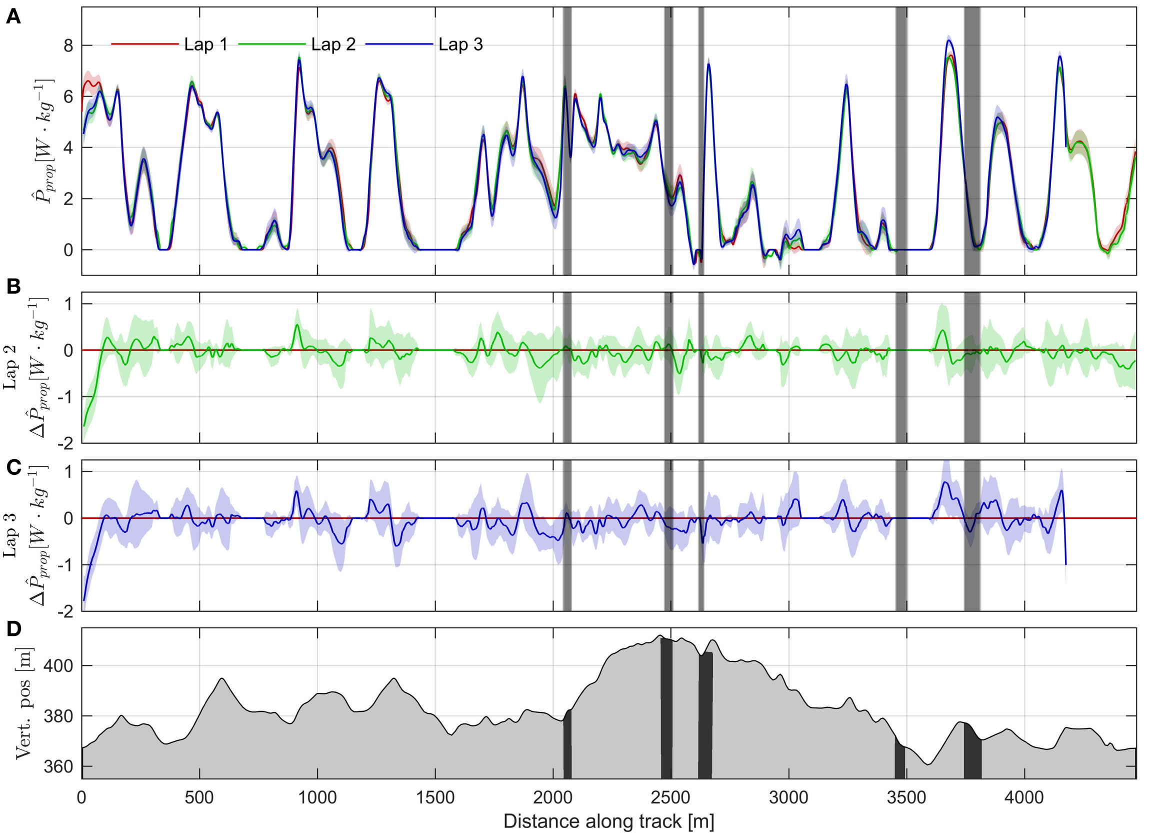


**FIGURE 4 | (A)** Propulsive power normalized to body mass plotted over distance along the course for the three laps (lap 1 red, lap 2 green, lap 3 blue). Colored regions around the solid lines show the standard deviations from the Monte Carlo simulation. Vertical gray shading indicates regions where double differenced ambiguities were float. The Monte Carlo simulation does not account for the reduced accuracy in these regions. Negative values of $P_{\text{prop}}$ occurs when $F_{\text{prop}} < 0$ and could be caused by either active breaking of the athlete, or by measurement error. **(B)** Mean difference in propulsive power between lap 2 and lap 1. Colored shaded region shows the 95% CI. **(C)** Same as B, but for the difference between lap 3 and lap 1. **(D)** Altitude profile of the competition course. Black regions correspond to the regions where double differenced ambiguities were float.

square (RMS) deviation of 1.25 W·kg$^{-1}$ from the more accurate method of using vertical position mapped onto the dGNSS measurements. This is about 30% of mean active propulsive power. Example data for these calculations from one of the athletes are shown in **Figure 9**. Omitting the accelerometer measurements by using frontal areas obtained from allometric scaling (Equation 6, **Figure 6**) yielded an RMS deviation of 0.18 W·kg$^{-1}$, or about 4% of mean active propulsive power (**Figure 9**).

Regression and curve fitting parameters for the frontal area model (Equation 5), drag coefficient model (Equation 8) and allometric scaling of frontal areas (Equation 6) are presented in **Table 1**.

## Environmental Conditions

Air temperature and air pressure on the three test days ranged from 12 to 13°C and 95.1–98.1 kPa, respectively. Average hourly wind speed from the two measurements stations ranged from 2.70 to 4.48 m·s$^{-1}$ (measured at 10 meters above ground), and average wind direction ranged from 14 to 46°.

# DISCUSSION

Accurate measurements of the propulsive power throughout a cross-country ski race could improve our understanding of the work requirements of cross-country skiing and other endurance sports that exhibit non-steady state power behavior (**Figure 10**). Calculations of propulsive power during cross-country skiing using the principle of power balance have been attempted by several authors (Moxnes and Hausken, 2008; Carlsson et al., 2011; Sandbakk et al., 2011; Moxnes et al., 2013, 2014; Swarén and Eriksson, 2017), but the accuracy of the method has not been thoroughly addressed. The current study addresses the accuracy obtained when applying the power balance principle to GNSS measurements during a roller skiing test race on a World Cup-like ski course. This was achieved using a Monte Carlo simulation sampling from the distributions of the most relevant sources of error (air drag, rolling resistance, variations in wind velocity), which enabled quantification of the method's accuracy throughout the course. Furthermore, the current study is the first to present continuous measurements of propulsive power throughout a test race in distance skiing (Sandbakk et al., 2011;

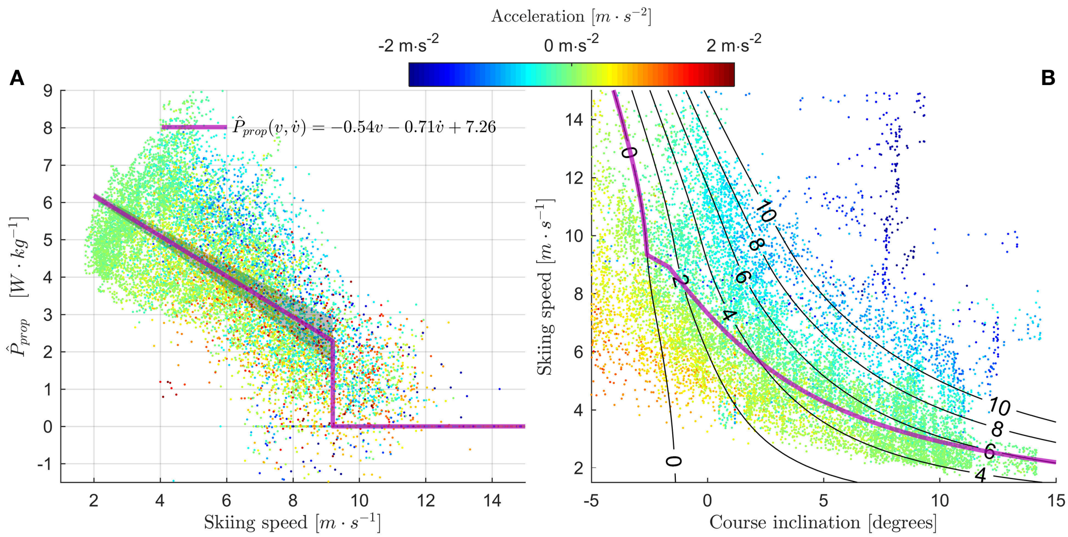


**FIGURE 5 | (A)** Propulsive power (normalized to body mass) was approximately linearly related to skiing speed ($v$) and acceleration ($\dot{v}$) in the skiing direction. Data from all athletes are included in the figure, and data points are color coded by $\dot{v}$, as indicated by the colorbar above the figure. The magenta-colored line is the least squares regression fit to samples where the athlete was not in the tucked position. The shaded region indicates the measurement error (SD), see **Figure 7** for details. **(B)** Plot of skiing speed vs. the course inclination. Data points are color coded as in panel **(A)**. The black lines indicate constant propulsive power (in W·kg$^{-1}$), assuming constant skiing speed ($\dot{v} = 0$). The magenta line shows the steady state skiing speed obtained from the regression line in (A). It was defined as the real root of the 3rd degree polynomial obtained by replacing $P_{prop}$ with $P_{prop}(v,\dot{v})$ in Equation 1, and assuming a constant drag area of 0.55 m$^2$ and average body mass 77.1 kg. For $v > 9$ m·s$^{-1}$ the line was defined to follow the zero-$P_{prop}$ iso-line. The figure clearly shows that data points where $\dot{v} \approx 0$ (green color) are distributed close to the steady-state speed line, as expected. Data points below the steady-state line have $\dot{v} > 0$ (red), and data points above the line have $\dot{v} < 0$. This is mainly attributed to the athletes' inertias.

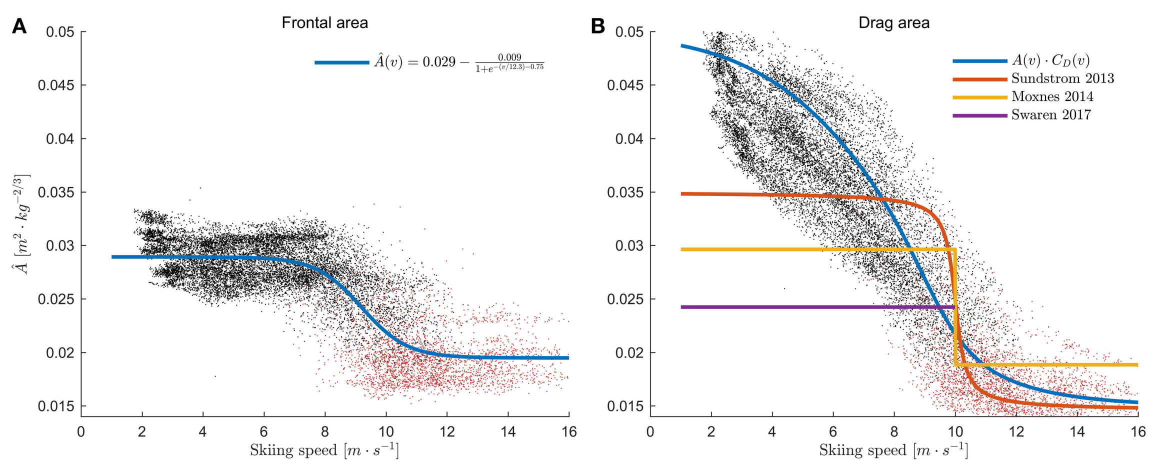


**FIGURE 6 | (A)** Frontal areas ($\hat{A}$) estimated from the accelerometer outputs plotted over skiing speed, normalized by body mass (using an allometric scaling coefficient of 2/3). Red dots represent measurements where the skiers were in the tucked position. Blue line: logistic function fitted to the data (Equation 6). Athletes typically assumed the tucked position at skiing speeds >9.1 m·s$^{-1}$. **(B)** Drag areas normalized to body mass ($\hat{A}{\cdot}C_D$) found in the current study plotted over skiing speed for all athletes. The blue line shows the product of the frontal area model from Equation 6 (plotted in panel A) and the drag coefficient (Equation 8, **Figure 2**). Models used by Sundström et al. (2013), Moxnes et al. (2014), and Swarén and Eriksson (2017) are included for comparison.

Swarén and Eriksson, 2017). Our findings show that the error in the propulsive power estimates increases with skiing speed, while the propulsive power generated by the athletes decreases approximately linearly as speed increases. They also show that a substantial part of the variability of $P_{prop}$ cannot be explained by skiing speed, accelerations, or measurement errors (**Figure 5A**). Explanations for this variability is most likely the complex course topography, which consisted of both relatively long uphill sections (i.e., from 2,000 to 2,500 m from the start, **Figure 4D**) and shorter uphill sections where the athletes had recovered

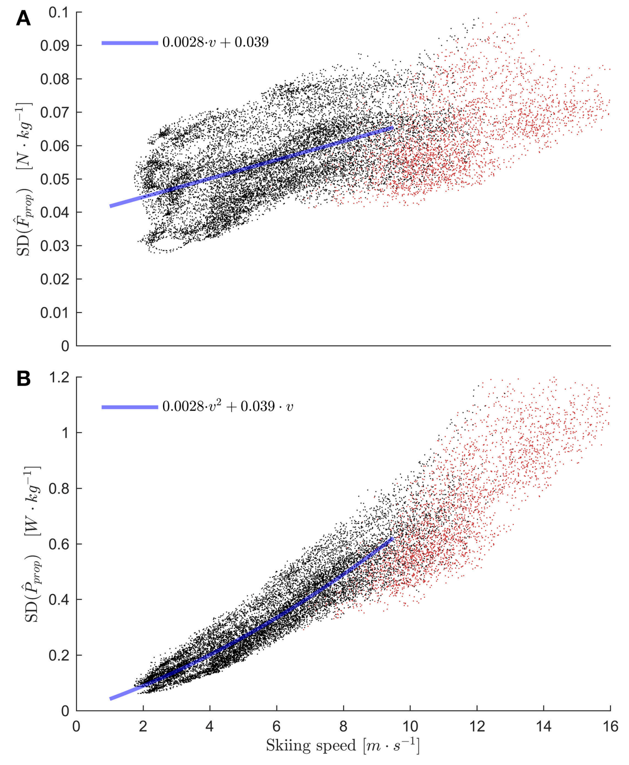


**FIGURE 7 | (A)** Standard deviation of propulsive force (normalized to body mass) calculated from the Monte Carlo simulation plotted over skiing speed. The red dots are measurements when the athletes were in the tucked position. In a later step propulsive power (and force) was defined to be zero for these samples, but they are included in this figure to illustrative purposes. The blue line is the least squares linear regression line fitted to the data points where the athletes were not in the tucked position. **(B)** same as **(A)**, but for $P_{prop}$. Since $P_{prop} = F_{prop} \cdot v$, the regression line from **(A)** multiplied with $v$ fits well to the data.

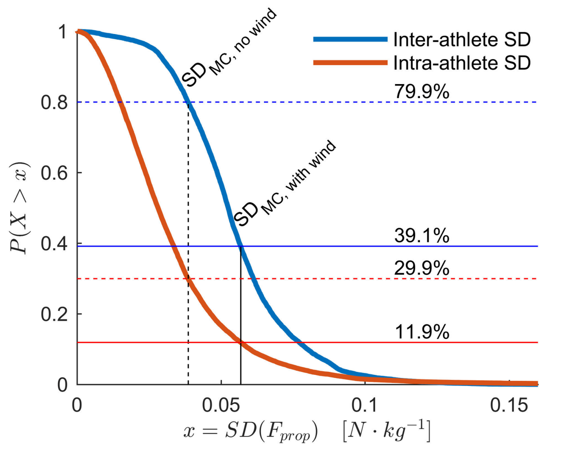


**FIGURE 8 |** In order to discriminate the $F_{prop}$ or $P_{prop}$ generated by high-level athletes, the methods accuracy must be better than typical athlete-to-athlete or within-athlete differences. To that end, this figure displays the empirical complementary cumulative distribution function (ECCDF) of typical athlete-to-athlete differences in $F_{prop}$ measured at the same position along the course (blue line). More specifically, it shows the between-athlete standard deviation of $F_{prop}$ evaluated at every integer meter along the course, excluding measurements where the athletes were in the tucked position. The red line is the ECCDF of the within-athlete lap-to-lap standard deviation. The solid vertical line at 0.0568 N·kg$^{-1}$ shows the mean standard deviation of $F_{prop}$ from the Monte Carlo simulation, which reflects the methods typical accuracy under the specified conditions. For comparison, the dotted vertical line at 0.0385 N·kg$^{-1}$ shows the mean standard deviation of $F_{prop}$ from another Monte Carlo simulation assuming zero-wind conditions. With the measured wind conditions, inter-athlete SD was greater than the typical measurement accuracy only for 39.1% of the course, and intra-athlete SD only for 11.9% of the course. Under the zero-wind assumption, the inter- and intra-athlete differences were greater than the measurement accuracy for 79.9 and 29.9% of the course, respectively.

during a long downhill section (3,600–3,730 m, **Figure 4D**). The duration of the longest uphill segment was typically ∼120 s, while the short uphill from 3,600 to 3,730 m after start was completed in slightly more than 20 s. During all-out running or cycling tests with durations of 120 and 20 s, the anaerobic energy contributions are approximately 37 and 82%, respectively (Gastin, 2001). Therefore, it is a reasonable assumption that during the longer uphill sections $P_{prop}$ is mainly limited by the athletes' $VO_{2,max}$, but this restriction does not apply to uphill sections with short durations, at least if the athletes are in a partially recovered state at the beginning of the uphill. This is in agreement with the observations in the current study, where $P_{prop}$ appeared to converge to ∼4 W·kg$^{-1}$ in the longest uphill while being almost 8 W·kg$^{-1}$ in the short uphill at 3,600–3,730 m after start.

The observation that propulsive power is higher at low skiing speeds is in agreement with the notion that skiers focus their effort on the uphill sections, where the external resistance is increased due to a substantial component of gravity along the skiing surface. Uphill terrain is also known to be the terrain that is the major determinant of overall performance during time trials (Andersson et al., 2010; Sandbakk et al., 2011, 2016b; Bolger et al., 2015). This is consistent with conclusions in both cycling and cross-country skiing suggesting that athletes should increase their work rate in course segments where the external resistance is increased (Swain, 1997; Atkinson et al., 2007; Sundström et al., 2013). The rationale for this is that a decline in speed over a given distance is not compensated by an equivalent increase in speed over the same distance. This implies that athletes should to some extent aim at minimizing variations in speed by varying the propulsive power.

The peak power outputs measured in the current study are substantially below the values reported by Swarén and Eriksson (2017), who reported peak power outputs of 16 W·kg$^{-1}$ for a male skier during a classical style sprint race. Because the athlete analyzed by Swarén and Eriksson (2017) was a high-level skier (qualified for the final in a Continental Cup race), it would be fair to compare that skier to the best ranked skier in the current study. The best ranked skier in the current study had <15 FIS-points at the time of the data collection, and a peak power output of 8.6 W·kg$^{-1}$, which is still substantially below the findings of Swarén and Eriksson (2017). In contrast, our findings show a

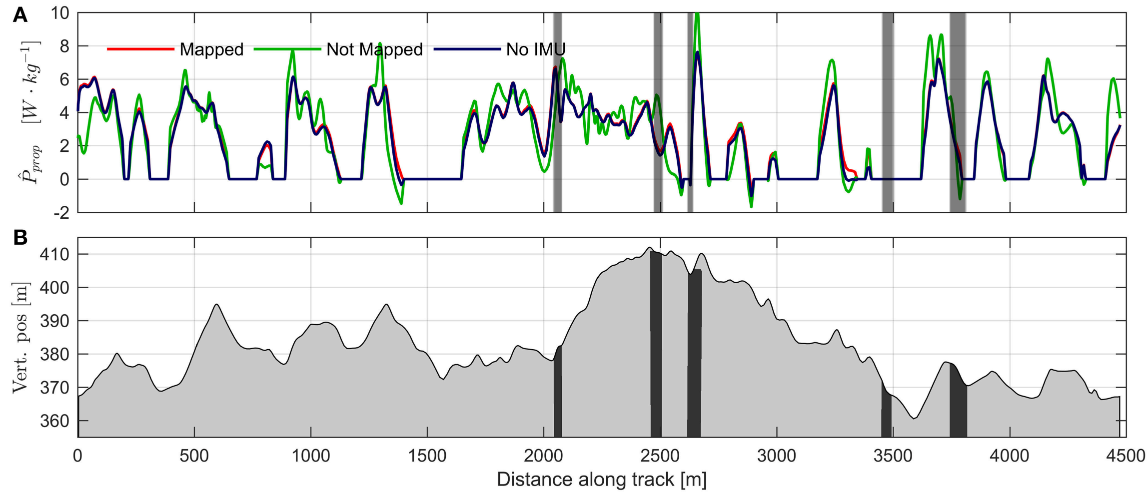


**FIGURE 9 | (A)** Comparison of propulsive power calculations using mapping on dGNSS reference (blue line), calculations using only measurements from the standalone GNSS receiver (green line), and using the simplified drag area model based on body mass and skiing speed (Equation 6, red line). Data are from one lap for a single athlete. Vertical gray shading indicates regions where double differenced ambiguities were float. **(B)** Altitude profile of the competition course. Black regions correspond to the regions where double difference ambiguities were float.

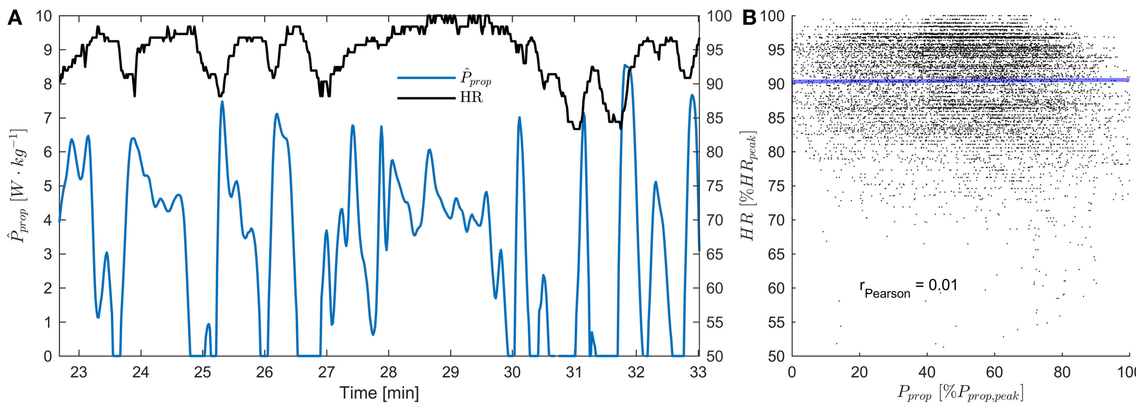


**FIGURE 10 | (A)** Heart rate (HR) and $P_{\text{prop}}$ measurements during the third lap for an example athlete. HR is expressed relative to the peak HR measured during the test race. **(B)** Scatter plot showing all measurements of $P_{\text{prop}}$ (normalized to each athlete's peak $P_{\text{prop}}$) vs. all measurements of HR. There was no significant correlation between the two parameters ($r_{\text{Pearson}} = 0.01$, $p = 0.18$). This indicates that changes in $P_{\text{prop}}$ during cross-country ski races are too fast for heart rate to provide a valid measure of instantaneous metabolic power.

larger power output than the segment average power of 5.76 W·kg$^{-1}$ found by Sandbakk et al. (2011) during a sprint skating race. However, this was the average power output over relatively long uphill section (duration of ~1 min) and is therefore difficult to compare directly.

The relationship between propulsive power and metabolic power during ski skating is non-trivial (Sandbakk et al., 2012; Andersson et al., 2017); therefore we cannot deduce directly from our measurements how the metabolic energy demand depends upon skiing speed. However, if we use the measurement of gross efficiency at an 8% incline and a high work rate ($\eta_{\text{Gross}} = 16.4$ %) from Sandbakk et al. (2012) as a basis, our findings suggests a typical metabolic power of about 38 W·kg$^{-1}$ at skiing speeds of 2 m·s$^{-1}$, which corresponds to an oxygen demand of about 108 mL·kg$^{-1}$·min$^{-1}$ (Péronnet and Massicotte, 1991). For the peak power output measured, the corresponding oxygen demand would be 147 mL·kg$^{-1}$·min$^{-1}$. Assuming a $\dot{V}O_{2,\text{peak}}$ for this level of skiers of 75 mL·kg$^{-1}$·min$^{-1}$, this corresponds to a typical oxygen demand of about 144% of peak aerobic power at 2 m·s$^{-1}$, and a peak oxygen demand of about 196% of peak aerobic power, and must therefore elicit substantial use of anaerobic energy pathways. This is in agreement with previous studies in both sprint skiing (Sandbakk et al., 2011) and distance skiing (Norman and Komi, 1987; Karlsson et al., 2018). It is interesting to note that the peak metabolic energy requirements in sprint skiing and distance skiing appear to be relatively similar, even though the competition duration is substantially different (∼2–4 min for sprint skiing and >30 min for a 15 km race). This might partly explain why cross-country skiing requires a relatively small degree of specialization to each discipline, allowing individual athletes to be world-class over distances ranging from ∼1.3 to 50 km.

## Methodological Considerations

The method's applicability to discriminate between $P_{\mathrm{prop}}$ and $F_{\mathrm{prop}}$ generated by high-level athletes depends on whether the measurement error is smaller than typical inter-athlete and intra-athlete differences observed throughout a race. Our findings show that the proposed method was not sufficiently accurate to discriminate between the inter-athlete or intra-athlete differences observed in this group of high-level skiers. The sources of these errors are distributed almost evenly between air drag (0.034 or 0.016 $\mathrm{N{\cdot}kg^{-1}}$ with measured wind and zero-wind, respectively) and rolling resistance (0.023 $\mathrm{N{\cdot}kg^{-1}}$). Because of varying surface-properties (i.e., asphalt quality) and the significant effect of temperature on the rolling resistance (Ainegren et al., 2008), it is challenging to obtain substantially more accurate measurements of rolling resistance. However, changes in rolling resistance caused by changes in asphalt quality or temperature will to some extent be systematic effects, and will therefore partially cancel when comparing intra- or inter-athlete differences during one experiment. Hence, the sensitivity-criterion used in the current study is appropriate when comparing results from different experiments, but might be too conservative for differences observed during a single experiment.

The results of this study clearly indicate the importance of precise measurements of vertical position. Estimates of propulsive power using vertical position measurements from the standalone GNSS receiver were substantially different (RMS deviation 31% of mean active propulsive power) from the measurements that were mapped onto the dGNSS reference trajectory. Hence, mapping standalone GNSS data on a precisely measured reference trajectory, or using athlete-mounted carrier phase differential GNSS receivers (Gilgien et al., 2014b; Karlsson et al., 2018) is required to calculate meaningful propulsive power measurements. Another solution that might be applicable is to fuse GNSS with IMU or barometric measurements (Skaloud and Limpach, 2003).

Predicting the drag area using only body mass and skiing speed yielded relatively small deviations from the accelerometer-based drag area model, and could therefore be an acceptable solution for many practical applications.

## Limitations

In the current study we used roller skiing as an analog exercise for cross-country skiing on snow. Furthermore, a test race was used rather than an official ski race. Hence, the current study has lower external validity than studies performed on snow (Sandbakk et al., 2011; Swarén and Eriksson, 2017), but has higher internal validity because rolling resistance could be measured more accurately than ski/snow friction, and was less likely to change substantially during the test race.

Another challenge when applying the power balance principle is to accurately calculate air drag, because the drag area and wind speed are difficult to measure continuously along the course. As indicated in **Figure 2**, the drag coefficient of a cross-country skier depends on the Reynolds number. However, measurements are scarce and inconsistent, particularly at Reynolds numbers $<2{\cdot}10^5$. In the current study we created a model for how the drag coefficient changes with Reynolds number based on measurements on a brass cylinder (Achenbach, 1968), and scaled it to fit previous measurements of ice skaters at 12 $\mathrm{m{\cdot}s^{-1}}$ (van Ingen Schenau et al., 1982). We chose not to base our model on the measurements in Spring et al. (1988), as their equations did not account for changes in gravitational potential energy that would be caused by a non-level rolling surface. This could lead to substantial errors, particularly at low skiing speeds, even if the inclination of the rolling surface is very small. As an example, a 0.1° incline at 3 $\mathrm{m{\cdot}s^{-1}}$ would result in an error in $C_{\mathrm{D}}A$ of ∼0.25 $\mathrm{m^2}$. Hence, wind-tunnel studies investigating how the drag coefficient of a cross-country skier depends upon the Reynolds number would be useful, particularly at conditions relevant for low skiing speeds.

A challenge that was not addressed in the drag coefficient model proposed in current study is that cross-country skiing techniques causes body segments to move with different speeds through the air. This effect is most pronounced for the ski poles, where the pole tip's speed varies from 0 (when in contact with the ground) to an unknown speed substantially higher than the skiing speed. However, as the cross-sectional area of ski poles are relatively small, it is likely that this has only a minor effect on the total drag area.

Wind velocity was not measured continuously along the course but was estimated by a wind field based on the hourly average of two nearby meteorological stations, and the assumption of a Rayleigh distribution. The Monte Carlo approach simulated a large number (2,500) of different wind conditions and returned the expected value from all the simulated conditions, which should improve the calculations with respect to the assumption of a constant wind field. Nonetheless, it is obvious that the instantaneous wind velocity is strongly affected by gusts and the proximate surroundings of the course, and our calculations are therefore susceptible to such errors. The errors should however be within the uncertainty bounds specified by the Monte Carlo simulation.

The point mass assumption used in the current study neglects the work required to move body segments with respect to the athlete's center of mass, and therefore does not represent the total mechanical work done by the athlete. It is likely that the total mechanical work substantially exceeds the work required to move the center of mass alone. However, calculation of total mechanical work requires measurements of both the moments of force in all joints and the body segment kinematics (Aleshinsky, 1986; van Ingen Schenau and Cavanagh, 1990). Such measurements are currently not possible, at least in a field situation. Furthermore, even if the total mechanical work could be measured, there is no theoretically valid method to calculate the metabolic energy requirements based on kinetics and kinematics alone. Nevertheless, this should not discourage the use of statistical models linking propulsive power or total mechanical power to metabolic power under the assumption that the model is proven accurate for the problem being studied.

Two additional sources of error that have not been assessed in this study are that the skis do not move the exact same distance as the center of mass (due to the ski skating technique) and the fact that a small fraction of the surface normal force is exerted through the poles (estimated to 3–5% of body weight Millet et al., 1998). These effects have been assessed in other studies (Losnegard et al., 2012; Sandbakk et al., 2012) and are considered to be only of minor consequence.

## Prospects

Studies in other winter sports where equipment-snow/ice friction and air drag are the main opposing forces have shown that the derivations of power, energy/work and propulsive force from athletes using position data are powerful approaches to studying the underlying mechanisms of performance (van Ingen Schenau et al., 1982; Supej, 2008; Gilgien et al., 2014a, 2016, 2018; Kröll et al., 2016). In endurance sports such as cross-country skiing, combining measurements of propulsive power with a model for skiing efficiency is a natural extension of the current study, and would improve our understanding of the physiological requirements of cross-country skiing (Sandbakk et al., 2011; Karlsson et al., 2018). Furthermore, simultaneous measurements of oxygen consumption would allow assessments of the balance between aerobic and anaerobic energy pathways at (or close to) the limit of human endurance racing performance (Andersson et al., 2017). Such measurements could also be used to improve numerical simulations of cross-country skiing performance (Moxnes et al., 2013, 2014), and to explore the effect of different pacing strategies (Swain, 1997; Sundström et al., 2013; Karlsson et al., 2018).

Although the Monte Carlo simulations used in the current study provides some insight into the method's validity and limitations, a validation against a gold standard has not been performed. Future studies could investigate the methods accuracy using ski poles and roller skis instrumented with force transducers.

## Conclusion

During a 13.5 km roller skiing test race on a course similar to a cross-country skiing World Cup competition course, elite cross-country skiers generated a propulsive power output that declined approximately linearly with skiing speed, starting from 6.2 $W \cdot kg^{-1}$ at the lowest measured speeds of 2.0 $m \cdot s^{-1}$ (occurring at inclinations $> \sim 10°$). At skiing speeds close to 9 $m \cdot s^{-1}$ and inclinations $< \sim -2°$ the skiers transitioned to the tucked position where no propulsive power was generated. Furthermore, the results of this study clearly indicate the importance of precise measurements of vertical position, and shows that standalone GNSS receivers are not sufficiently accurate to be used for propulsive power calculations unless the measurements are mapped on a precisely measured reference trajectory, or replaced by carrier phase differential GNSS receivers. In contrast, predictions of drag area using only body mass and skiing speed deviated only slightly from those based on accelerometer data and should be acceptable for many practical applications. However, none of the methods presented in the current study were sufficiently accurate to discriminate between the instantaneous differences in propulsive force in this group of high-level athletes.

## AUTHOR CONTRIBUTIONS

Conception and design: ØG, TL, MG, DD, and AM-S. Data collection and data analysis: ØG and MG. Manuscript draft of Introduction: ØG and MG. Manuscript draft of Methods, Results, and Discussion: ØG. All authors contributed to manuscript revision, and read and approved the submitted version.

## FUNDING

This study was funded by the Norwegian School of Sports Sciences, Oslo, Norway, and the Norwegian Research Council (project 216699).

## REFERENCES

Achenbach, E. (1968). Distribution of local pressure and skin friction around a circular cylinder in cross-flow up to Re = $5*10^6$. *J. Fluid Mech* 34, 625–639. doi: 10.1017/S0022112068002120

Ainegren, M., Carlsson, P., and Tinnsten, M. (2008). Rolling resistance for treadmill roller skiing. *Sport. Eng.* 11, 23–29. doi: 10.1007/s12283-008-0004-1

Aleshinsky, S. Y. (1986). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem. *J. Biomech.* 19, 287–315.

Andersson, E., Björklund, G., Holmberg, H.-C., and Ørtenblad, N. (2017). Energy system contributions and determinants of performance in sprint cross-country skiing. *Scand. J. Med. Sci. Sports* 27, 385–398. doi: 10.1111/sms.12666

Andersson, E., Supej, M., Sandbakk, Ø., Sperlich, B., Stoggl, T., and Holmberg, H. C. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur. J. Appl. Physiol.* 110, 585–595. doi: 10.1007/s00421-010-1535-2

Atkinson, G., Peacock, O., and Passfield, L. (2007). Variable versus constant power strategies during cycling time-trials: prediction of time savings using an up-to-date mathematical model. *J. Sports Sci.* 25, 1001–1009. doi: 10.1080/02640410600944709

Bergh, U. (1987). The influence of body mass in cross-country skiing. *Med. Sci. Sports Exerc.* 19, 324–331.

Bolger, C. M., Kocbach, J., Hegge, A. M., and Sandbakk, Ø. (2015). Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int. J. Sports Physiol. Perform.* 10, 873–880. doi: 10.1123/ijspp.2014-0335

Bowden, F. P., and Hughes, T. P. (1939). The mechanism of sliding on ice and snow. *Proc. R. Soc. A Math. Phys. Eng. Sci.* 172, 280–298. doi: 10.1098/rspa.1939.0104

Buhl, D., Fauve, M., and Rhyner, H. (2001). The kinetic friction of polyethylen on snow: the influence of the snow temperature and the load. *Cold Reg. Sci. Technol.* 33, 133–140. doi: 10.1016/S0165-232X(01)00034-9

Canuto, C., Quarteroni, A., Hussaini, M. Y., and Zang, T. A. (2007). *Fundamentals of Fluid Dynamics*. New York, NY: Springer.

Carlsson, P., Tinnsten, M., and Ainegren, M. (2011). Numerical simulation of cross-country skiing. *Comput. Methods Biomech. Biomed. Engin.* 14, 741–746. doi: 10.1080/10255842.2010.493885

Dooner, D. B. (2012). *Kinematic Geometry of Gearing*. Chichester, UK: John Wiley & Sons

Dorvlo, A. S. S. (2002). Estimating wind speed distribution. *Energy Convers. Manag.* 43, 2311–2318. doi: 10.1016/S0196-8904(01)00182-0

Ettema, G., and Lorås, H. W. (2009). Efficiency in cycling: a review. *Eur. J. Appl. Physiol.* 106, 1–14. doi: 10.1007/s00421-009-1008-7

Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sport. Med.* 31, 725–741. doi: 10.2165/00007256-200131100-00003

Gilat, A., and Subramaniam, V. (2008). *Numerical Methods for Engineers and Scientists*, *3rd Edn.* Hoboken: NJ: John Wiley & Sons.

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: Basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Spörri, J., Kröll, J., Crivelli, P., and Müller, E. (2014a). Mechanics of turning and jumping and skier speed are associated with injury risk in men's World Cup alpine skiing: a comparison between the competition disciplines. *Br. J. Sports Med.* 48, 724–747. doi: 10.1136/bjsports-2013-092994

Gilgien, M., Spörri, J., Kröll, J., and Müller, E. (2016). Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing. *Br. J. Sports Med.* 50, 8–13. doi: 10.1136/bjsports-2015-095465

Gilgien, M., Spörri, J., Limpach, P., Geiger, A., and Müller, E. (2014b). The effect of different global navigation satellite system methods on positioning accuracy in elite alpine skiing. *Sensors* 14, 18433–18453. doi: 10.3390/s141018433

Günther, B. (1975). Dimensional analysis and theory of biological similarity. *Physiol. Rev.* 55, 659–699. doi: 10.1152/physrev.1975.55.4.659

Haugen, T., Paulsen, G., Seiler, S., and Sandbakk, Ø. (2017). New records in human power. *Int. J. Sports Physiol. Perform.* 13, 678–686. doi: 10.1123/ijspp.2017-0441

Hoffman, M. D., Clifford, P. S., Bota, B., Mandli, M., and Jones, G. M. (1990). Influence of body mass on energy cost of roller skiing. *Int. J. Sport Biomech.* 6, 374–385. doi: 10.1123/ijsb.6.4.374

Ingjer, F. (1991). Maximal oxygen uptake as a predictor of performance ability in women and men elite cross-country skiers. *Scand. J. Med. Sci. Sports* 1, 25–30. doi: 10.1111/j.1600-0838.1991.tb00267.x

Karlsson, Ø., Gilgien, M., Gløersen, Ø., Rud, B., and Losnegard, T. (2018). Exercise intensity during cross-country skiing described by oxygen demands in flat and uphill terrain. *Front. Physiol.* 9:846. doi: 10.3389/fphys.2018.00846

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016). Sidecut radius and kinetic energy: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 26–31. doi: 10.1136/bjsports-2015-095463

Losnegard, T., and Hallén, J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *Int. J. Sports Physiol. Perform.* 9, 25–31. doi: 10.1123/ijspp.2013-0066

Losnegard, T., Myklebust, H., and Hallén, J. (2012). Anaerobic capacity as a determinant of performance in sprint skiing. *Med. Sci. Sports Exerc.* 44, 673–681. doi: 10.1249/MSS.0b013e3182388684

Millet, G. Y., Boissiere, D., and Candau, R. (2003). Energy cost of different skating techniques in cross-country skiing. *J. Sports Sci.* 21, 3–11. doi: 10.1080/0264041031000070903

Millet, G. Y., Hoffman, M. D., Candau, R. B., and Clifford, P. S. (1998). Poling forces during roller skiing: effects of technique and speed. *Med. Sci. Sports Exerc.* 30, 1645–1653. doi: 10.1097/00005768-199811000-00014

Moxnes, J. F., and Hausken, K. (2008). Cross-country skiing motion equations, locomotive forces and mass scaling laws. *Math. Comput. Model. Dyn. Syst.* 14, 535–569. doi: 10.1080/13873950802164643

Moxnes, J. F., Sandbakk, Ø., and Hausken, K. (2013). A simulation of cross-country skiing on varying terrain by using a mathematical power balance model. *Open Access J. Sport. Med.* 4, 127–139. doi: 10.2147/OAJSM.S39843

Moxnes, J. F., Sandbakk, Ø., and Hausken, K. (2014). Using the power balance model to simulate cross-country skiing on varying terrain. *Open access J. Sport. Med.* 5, 89–98. doi: 10.2147/OAJSM.S53503

Myklebust, H. (2016). *Quantification of Movement Patterns in Cross-Country Skiing Using Inertial Measurement Units*. Dr. Thesis, Norwegian School of Sport Sciences.

Myklebust, H., Gløersen, Ø., and Hallén, J. (2015). Validity of ski skating center of mass displacement measured by a single inertial measurement unit. *J. Appl. Biomech.* 31, 492–498. doi: 10.1123/jab.2015-0081

Norman, R. W., and Komi, P. V. (1987). Mechanical energetics of world class cross-country skiing. *Int. J. Sport Biomech.* 3, 353–369. doi: 10.1123/ijsb.3.4.353

Oke, T. R. (1978). *Boundary Layer Climates*, *2nd Edn*. London: Methuen.

Péronnet, F., and Massicotte, D. (1991). Table of nonprotein respiratory quotient : an update. *Can. J. Sport Sci.* 16, 23–29.

Sandbakk, Ø., Ettema, G., and Holmberg, H.-C. (2012). The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. *Eur. J. Appl. Physiol.* 112, 2829–2838. doi: 10.1007/s00421-011-2261-0

Sandbakk, Ø., Ettema, G., Leirdal, S., Jakobsen, V., and Holmberg, H.-C. (2011). Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur. J. Appl. Physiol.* 111, 947–957. doi: 10.1007/s00421-010-1719-9

Sandbakk, Ø., Hegge, A. M., Losnegard, T., Skattebo, Ø., Tønnessen, E., and Holmberg, H.-C. (2016a). The physiological capacity of the world's highest ranked female cross-country skiers. *Med. Sci. Sports Exerc.* 48, 1091–1100. doi: 10.1249/MSS.0000000000000862

Sandbakk, Ø., and Holmberg, H.-C. (2014). A Reappraisal of Success factors for olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sandbakk, Ø., Losnegard, T., Skattebo, Ø., Hegge, A. M., Tønnessen, E., and Kocbach, J. (2016b). Analysis of classical time-trial performance and technique-specific physiological determinants in elite female cross-country skiers. *Front. Physiol.* 7:326. doi: 10.3389/fphys.2016.00326

Skaloud, J., and Limpach, P. (2003). "Synergy of CP-DGPS, accelerometry and magnetic sensors for precise trajectography in ski Racing," in *Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS)* (Portland, OR).

Spring, E., Savolainen, S., Erkkilä, J., Hämäläinen, T., and Pihkala, P. (1988). Drag area of a cross-country skier. *Int. J. Sport Biomech.* 4, 103–113. doi: 10.1123/ijsb.4.2.103

Spurk, H., and Aksel, N. (2008). *Fluid Mechanics, 2 Edn*. Berlin: Springer-Verlag.

Sundström, D., Carlsson, P., Ståhl, F., and Tinnsten, M. (2013). Numerical optimization of pacing strategy in cross-country skiing. *Struct. Multidiscip. Optim.* 47, 943–950. doi: 10.1007/s00158-012-0856-7

Supej, M. (2008). Differential specific mechanical energy as a quality parameter in racing alpine skiing. *J. Appl. Biomech.* 24, 121–129. doi: 10.1123/jab.24.2.121

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Med. Sci. Sports Exerc.* 29, 1104–1108.

Swarén, M., and Eriksson, A. (2017). Power and pacing calculations based on real-time locating data from a cross-country skiing sprint race. *Sport. Biomech.* 3141, 1–12. doi: 10.1080/14763141.2017.1391323

Theile, T., Szabo, D., Luthi, A., Rhyner, H., and Schneebeli, M. (2009). Mechanics of the ski–snow contact. *Tribol. Lett.* 36, 223–231. doi: 10.1007/s11249-009-9476-9

van Ingen Schenau, G. J., and Cavanagh, P. R. (1990). Power equations in endurance sports. *J. Biomech.* 23, 865–881. doi: 10.1016/0021-9290(90)90352-4

van Ingen Schenau, G. J., Ohtsuki, T., Cruz, J. C., Hogan, R. P., and Balke, B. (1982). The influence of air friction in speed skating. *J. Biomech.* 15, 449–458. doi: 10.1016/0021-9290(82)90081-1

Welde, B., Evertsen, F., Von Heimburg, E., and Ingulf Medbø, J. (2003). Energy cost of free technique and classical cross-country skiing at racing speeds. *Med. Sci. Sport. Exerc.* 35, 818–825. doi: 10.1249/01.MSS.0000064936.04725.FD

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 17 May 2018
doi: 10.3389/fphys.2018.00570

# Macro-Kinematic Differences Between Sprint and Distance Cross-Country Skiing Competitions Using the Classical Technique

**Finn Marsland[1,2]*, Judith Anson[1], Gordon Waddington[1], Hans-Christer Holmberg[3,4] and Dale W. Chapman[1,2]**

[1] UC Research Institute for Sport and Exercise, University of Canberra, Canberra, ACT, Australia, [2] Australian Institute of Sport, Canberra, ACT, Australia, [3] The Swedish Winter Sports Research Centre, Mid-Sweden University, Östersund, Sweden, [4] School of Sport Sciences, UiT The Arctic University of Norway, Tromsø, Norway

OPEN ACCESS

**Edited by:**
Gregoire P. Millet,
Université de Lausanne, Switzerland

**Reviewed by:**
Beat Knechtle,
University Hospital Zurich, Switzerland
Guilaume Millet,
University of Calgary, Canada

***Correspondence:**
Finn Marsland
finn.marsland@gmail.com

**Specialty section:**
This article was submitted to
Exercise Physiology,
a section of the journal
Frontiers in Physiology

**Received:** 19 January 2018
**Accepted:** 30 April 2018
**Published:** 17 May 2018

**Citation:**
Marsland F, Anson J, Waddington G, Holmberg H-C and Chapman DW (2018) Macro-Kinematic Differences Between Sprint and Distance Cross-Country Skiing Competitions Using the Classical Technique. Front. Physiol. 9:570. doi: 10.3389/fphys.2018.00570

We compare the macro-kinematics of six elite female cross-country skiers competing in 1.1-km Sprint and 10.5-km Distance classical technique events on consecutive days under similar weather and track conditions. The relative use of double pole (DP), kick-double pole (KDP), diagonal stride (DS), tucking (Tuck) and turning (Turn) sub-techniques, plus each technique's respective velocities, cycle lengths and cycle rates were monitored using a single micro-sensor unit worn by each skier during the Sprint qualification, semi-final and finals, and multiple laps of the Distance race. Over a 1.0-km section of track common to both Sprint and Distance events, the mean race velocity, cyclical sub-technique velocities, and cycle rates were higher during the Sprint race, while Tuck and Turn velocities were similar. Velocities with KDP and DS on the common terrain were higher in the Sprint (KDP +12%, DS +23%) due to faster cycle rates (KDP +8%, DS +11%) and longer cycle lengths (KDP +5%, DS +10%), while the DP velocity was higher (+8%) with faster cycle rate (+16%) despite a shorter cycle length (−9%). During the Sprint the percentage of total distance covered using DP was greater (+15%), with less use of Tuck (−19%). Across all events and rounds, DP was the most used sub-technique in terms of distance, followed by Tuck, DS, Turn and KDP. KDP was employed relatively little, and during the Sprint by only half the participants. Tuck was the fastest sub-technique followed by Turn, DP, KDP, and DS. These findings reveal differences in the macro-kinematic characteristics and strategies utilized during Sprint and Distance events, confirm the use of higher cycle rates in the Sprint, and increase our understanding of the performance demands of cross-country skiing competition.

**Keywords: kinematics, cycle length, cycle rate, performance analysis, wearable sensors, Winter Olympics**

## INTRODUCTION

From its early beginnings in the late 1990s, the cross-country (XC) skiing sprint event (Sprint) has become a regular feature at all levels of International Ski Federation (FIS) international competition. Indeed, Sprint events (including the Team-Sprint) now constitute more than 30% of the total events on the World Cup circuit, one third of individual events at the World Junior and

U23 Championships, and one third of events at the Winter Olympics and World Championships (FIS, 2017).

FIS Sprint events can be between 800 and 1800 m in length, typically taking 2 – 4 min to complete. This contrasts with traditional distance XC skiing events (Distance), which range from 5 to 30 km for women and 10 – 50 km for men at the World Championship and Winter Olympic levels, and can be as long as 90 km on the ski marathon circuit (FIS, 2018). It is thus not surprising that Sprint and Distance specialists have developed, although there remain "all-rounders" who contend for medals in both categories (Sandbakk et al., 2010; Sandbakk and Holmberg, 2014).

Over the past decade or so, several key studies have expanded our insight into Sprint performance (Zory et al., 2005; Stöggl et al., 2007; Vesterinen et al., 2009; Andersson et al., 2010; Sandbakk et al., 2011, 2012b). Examining physiological and kinematic responses during a simulated classic Sprint competition on a treadmill, Stöggl et al. (2007) concluded that performance depends not only on physiological factors such as anaerobic capacity and fatigue resistance, but also on the technique used as skiers who were able to utilize the double pole (DP) sub-technique longer performed better. This connection between choice of sub-technique and performance was confirmed by Andersson et al. (2010), who reported that during a simulated freestyle Sprint competition on snow the fastest skiers used a "higher gear" (G3 over G2 technique) to a greater extent. These XC skiing macro-kinematic variables – the relative use of each sub-technique, as well as the associated velocities, cycle lengths and cycle rates – are adapted continuously by each competitor in response to the varying terrain and conditions during a competition, within the constraints of their own strengths/weaknesses and/or personal preference (Myklebust et al., 2011; Sandbakk et al., 2011; Marsland et al., 2017).

Andersson et al.'s (2010) investigation was the first to assess macro-kinematics over the entire length of an on-snow competition. Previous kinematic analyses of this nature focussed on these parameters only for short sections of track using video analysis (Smith and Heagy, 1994; Bilodeau et al., 1996), and, more recently, force plates under the snow (Mikkola et al., 2013; Andersson et al., 2014). Velocities for different sections of a course have been reported, though without examining the relative usage of specific sub-techniques (Sandbakk et al., 2011, 2016; Bolger et al., 2015).

Recent developments in micro-sensor technology provide novel possibilities for performance analysis in the field, enabling XC skiing macro-kinematics to be monitored continuously over an entire course (Myklebust et al., 2011; Sakurai et al., 2014, 2016; Marsland et al., 2017). This technology is still developing, with different micro-sensor configurations being investigated (Stöggl et al., 2014; Rindal et al., 2017; Seeberg et al., 2017), and to date only limited full competition data have been reported. The greatest challenge in comparing events at different locations is that the topography of each course is unique, and, moreover, snow conditions even at the same location can vary considerably from day to day (Wagner and Horel, 2011). Previous work by the authors revealed that macro-kinematic strategies also vary for each individual skier (Marsland et al., 2017).

The present study was designed to compare and contrast macro-kinematic variables utilized by the same athletes under similar conditions for both Sprint and Distance competitions. By comparing data collected from the same section of track involved in both events, we sought to provide new insights into the demands of XC skiing competition. We anticipated that velocities and cycle rates would be greater during the Sprint competition than the Distance event, and that differences in cycle lengths and the relative use of each sub-technique would be apparent. Furthermore, this work would increase the limited amount of published competition data available on female skiers, and facilitate characterisation and subsequent comparison as more findings are reported.

## MATERIALS AND METHODS

### Participants

Six female XC skiers participated, including two medallists at the World Cup or World Championship level (**Table 1**) and four Winter Olympians. All of these athletes volunteered to participate after being contacted via their team coach and were provided with written information about the study and given the opportunity to ask questions. Each athlete provided her written informed consent prior to participation, with ethical approval provided by the University of Canberra Committee for Ethics in Human Research and the Australian Institute of Sport Ethics Committee.

### Equipment

A single micro-sensor unit (MinimaxX$^{TM}$ S4, Catapult Innovations, Melbourne, Australia) containing a triaxial accelerometer (100 Hz, ±6 g), gyroscope (100 Hz, ±1,000 d/s) and a GPS device (Fastrax, 10 Hz) was secured to the middle of the upper back using a thin chest harness. This unit was positioned as described by Marsland et al. (2012), and calibrated according to Harding et al. (2008).

### Study Design

Data were collected during FIS Sprint and Distance competitions held on consecutive days. These race courses were designed by the organizing committee according to FIS homologation rules using the available terrain, and were approved for FIS international competition. Data were collected as the skiers covered the Sprint and Distance race courses, which included a common section of track approximately 1.0-km long. This section contained three uphill (total climb 27 m) and three downhill segments, as well as a long straight section leading into the finishing/lap area

**TABLE 1** | Characteristics of the participants (means ± SD).

| Characteristics | Values (*n* = 6) |
|---|---|
| Age (years) | 24.8 ± 4.4 |
| Body height (m) | 1.66 ± 0.06 |
| Body weight (kg) | 56.7 ± 5.2 |
| FIS Sprint rank (points) | 83.9 ± 64.6 |
| FIS Distance rank (points) | 65.6 ± 45.2 |

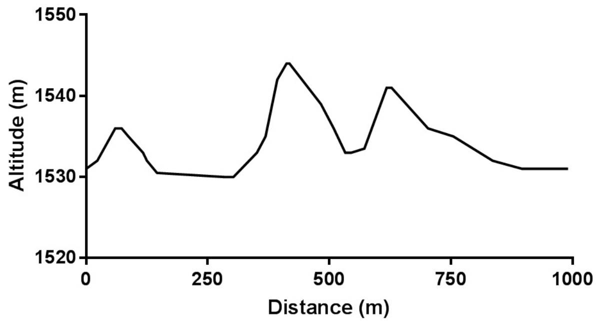


**FIGURE 1 |** Altitude profile for the common terrain.

(**Figure 1**). The Sprint race was approximately 1.1-km in length (total climb 27 m), while the 10.5-km Distance event involved three laps of a loop approximate 3.5-km long (total climb per lap 85 m).

In the Sprint all skiers competed in a qualification round (where they were seeded on the basis of their FIS points, the highest ranking starting first), after which the best twelve were seeded into two semi-final rounds. The fastest two skiers from each semi-final, plus the next two fastest skiers from either semi-final, progressed through to an A-final, following the same procedure as used for FIS World Cup events. The remaining skiers from the semi-final rounds competed in a B-final race. All the participating skiers were monitored during all three rounds of racing (qualification, semi-final and A- or B-final). Ninety minutes elapsed between the start of the qualification round and start of the finals, which were completed within 45 min.

The Distance event, held the day after the Sprint competition with similar snow conditions, began with a mass start, with the highest-ranked skiers seeded at the front. The snow temperature in the stadium varied between −2° and −1°, with the air temperature warming from −2° to +2°. The courses were prepared by an experienced snow groomer using a Piston Bully machine, and the tracks were firm. All skiers used their own equipment, with ski waxing by their personal coaches, who indicated that they used the same glide wax on both days.

## Classification of Technique

Data from the micro-sensors was imported into analytical software (Makesens V70.6, Appsen, Canberra, ACT, Australia), which classified the sub-technique employed as double pole (DP), kick-double pole (KDP), diagonal stride (DS), tucking (Tuck) or turning (Turn). DP involves simultaneous pushing with both arms with no propulsion from the legs; KDP has a kick from one leg added in the middle of the DP cycle; DS involves kicking with one leg and pushing with the opposite arm in an alternating manner. All these three cyclical techniques were identified using an algorithm based on filtered gyroscope and accelerometer signals, predominantly using consecutive peaks in the Pitch gyroscope signal filtered at 1 Hz in the manner described by Marsland et al. (2015). Turn was identified using the rate of change of GPS direction. Tuck is when a skier is in an aerodynamic bent-over position, and was detected through filtered accelerometer signals. These classifications were subsequently manually checked for errors by a cross-country skiing coach with extensive experience of evaluating such micro-sensor data, using a spreadsheet (Excel 2010, Microsoft, Seattle, WA, United States) together with visual analysis of plots of the accelerometer and gyroscope values. If there was any doubt, the sub-technique was classified as miscellaneous (Misc). For each cyclical sub-technique a full cycle was defined as lasting from one pole plant to the next pole plant on the same side (Marsland et al., 2017).

## Statistical Analyses

The Wilcoxon matched-pair non-parametric test was used to compare the mean kinematic parameters associated with the Sprint and Distance events, with the mean differences (MDiff) expressed as percentages and an alpha level of $p = 0.1$ to reduce the likelihood of a type II statistical error. Macro-kinematic variables were averaged across the three Sprint rounds, and for the common terrain across the second and third laps of the Distance race (the first lap was not analyzed because of differences in the course related to the mass start). Statistical analyses were performed using GraphPad Prism (GraphPad Software, La Jolla, CA, United States) and Excel 2010 software. Unless otherwise stated, all values are presented as mean ± SD.

# RESULTS

## Full Course

There was no statistically significant difference in the mean overall velocity of the skiers participating in the entire 1.1-km Sprint and 10.5-km Distance events, and mean finishing times across the rounds of the Sprint event also did not differ (**Table 2**). Skiers changed sub-technique an average of 16 ± 2 times (14.4 per km) during each of the Sprint rounds and 192 ± 23 times (18.4 per km) during the Distance race.

By distance, DP was utilized to the greatest extent for both the 1.1-km Sprint rounds and the 10.5-km event, followed by Tuck, DS and Turn, with KDP being employed least and only by three participants during the Sprint (**Table 3**).

Macro-kinematic variables for each round of the Sprint finals (not presented) were similar to the Sprint qualification round. In all cases, the velocity was fastest when using the Tuck sub-technique, followed by Turn, DP, KDP, and DS, in that order

**TABLE 2 |** Overall mean velocities and finishing times for the entire course Sprint and Distance races.

| | Distance (10.5-km) | Sprint (1.1-km) | | |
|---|---|---|---|---|
| | | Time-Trial | Semi-Final | Final |
| Velocity (m·s$^{-1}$) | 5.5 ± 0.4 | 5.7 ± 0.2 | 5.7 ± 0.1 | 5.7 ± 0.2 |
| [min–max] | [4.7–5.7] | [5.4–6.0] | [5.5–5.9] | [5.5–5.9] |
| Finishing time (s) | 1926 ± 125 | 195 ± 9 | 196 ± 4 | 195 ± 7 |
| [min–max] | [1860–2180] | [188–210] | [192–202] | [189–206] |

**TABLE 3 |** Velocities, cycle lengths and cycle rates, and usage by distance and time (mean ± SD), with the various sub-techniques for all three Sprint rounds (SP) and the 10.5-km Distance event (DI).

| | Velocity ($m \cdot s^{-1}$) | | Cycle length (m) | | Cycle rate ($cycle \cdot min^{-1}$) | | Usage by distance (%) | | Usage by time (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Technique** | **SP** | **DI** | **SP** | **DI** | **SP** | **DI** | **SP** | **DI** | **SP** | **DI** |
| DP | 6.1 ± 0.2** | 5.5 ± 0.3 | 5.3 ± 0.4** | 5.7 ± 0.3 | 69.6 ± 4.2** | 59.1 ± 4.1 | 54 ± 3** | 49 ± 4 | 51 ± 4 | 48 ± 4 |
| DS | 3.2 ± 0.2^ | 3.0 ± 0.2 | 2.5 ± 0.1** | 2.8 ± 0.1 | 80.6 ± 2.8** | 68.9 ± 3.4 | 13 ± 1* | 10 ± 2 | 22 ± 2* | 18 ± 4 |
| KDP# | 4.5 ± 0.2 | 4.2 ± 0.2 | 5.3 ± 0.4 | 5.2 ± 0.1 | 50.7 ± 3.1 | 48.7 ± 1.6 | 1 ± 2** | 4 ± 2 | 1 ± 3** | 5 ± 2 |
| Tuck | 9.1 ± 0.3** | 8.8 ± 0.1 | – | – | – | – | 14 ± 3** | 20 ± 2 | 9 ± 2** | 12 ± 1 |
| Turn | 7.8 ± 0.5** | 5.7 ± 0.4 | – | – | – | – | 9 ± 2* | 8 ± 0.3 | 6 ± 2** | 7 ± 0.3 |

***p = 0.03 compared to the other event, *p = 0.06 compared to the other event, ^p = 0.09 compared to the other event, #KDP was used by only 3 participants in the 1.1-km event.*

(**Table 3**). The mean velocities with Tuck, Turn, DP, and DS were significantly higher for the Sprint, with no difference for KDP. During the Sprint the DP and DS cycle rates were significantly higher, and the DP and DS cycle lengths significantly lower, compared to the Distance event, with similar values in each event observed for KDP.

## Common Terrain

The mean velocities achieved by the skiers on the common terrain during the second and third laps of the Distance race were 5.3 ± 0.4 m $s^{-1}$ (range 4.5–5.5) and 5.3 ± 0.5 m $s^{-1}$ (range 4.4–5.8) respectively. In comparison, the overall velocities for the Sprint qualification, semi-final and final rounds were 5.8 ± 0.2 m $s^{-1}$ (range 5.5–6.1), 5.8 ± 0.1 m $s^{-1}$ (range 5.6–5.9) and 5.8 ± 0.2 m $s^{-1}$ (range 5.5–6.0) respectively. Interestingly, the range in this velocity was narrower during the Sprint semi-final. On the common terrain there were sub-technique transitions 14 ± 2 times during the Sprint rounds and 15 ± 2 times during the Distance laps.

When on common terrain the sub-technique DP was utilized to the greatest extent, followed by Tuck, Turn (not presented) and DS (**Figure 2**), with KDP being employed least and only by three participants during the Sprint. The percentage of the total distance covered using DP was greatest in the Sprint (SP 50% v DI 43%, $p = 0.03$, MDiff = 15%), with a similar drop in the proportion of total time (SP 47% v DI 40%, $p = 0.03$, MDiff = 15%). With DS, the % distance was similar for both events, but percentage time was lower during the Sprint event as a consequence of the higher velocity (SP 25% v DI 28%, $p = 0.09$, MDiff = −10%). The time spent using Tuck was similar for both Sprint and Distance races, with slightly more rapid mean Distance velocity resulting in a longer distance (SP 16% v DI 19%, $p = 0.03$, MDiff = −19%). Mean KDP in usage was similar for both time and distance during both events. In terms of distance, unclassified techniques (Misc) were employed during 10 ± 3% of the Sprint event and 14 ± 2% of the Distance event. Regarding the Misc category, 3% of this in Sprint and 4% in Distance were attributed to transitions between sub-techniques, while 4% in Sprint and 6% in Distance were irregularities associated with Turns (i.e., where the skier had stopped performing a specified technique without yet beginning to change direction or had finished changing direction but not yet begun skiing with a specified technique again.

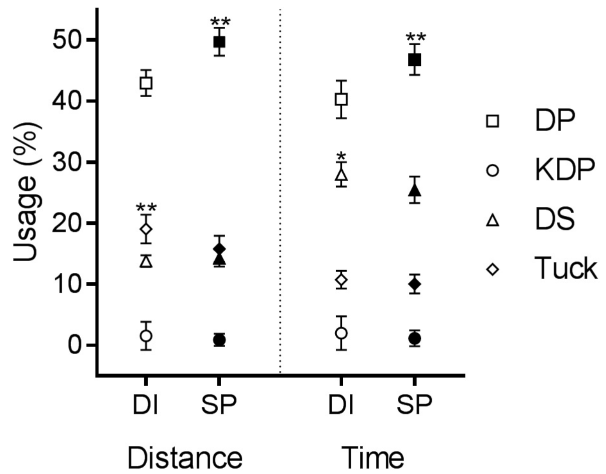


**FIGURE 2 |** Sub-technique usage (%) in terms of distance and time on the 1.0 km of common terrain ($n = 6$). Open symbols, Distance; closed symbols, Sprint. **$p = 0.03$ compared to the other event, *$p = 0.09$ compared to the other event.

Sub-technique velocities on the common terrain exhibited the same relative rank as for the entire course (**Figure 3**). During the Sprint the mean velocities for DP (6.2 ± 0.2 v 5.7 ± 0.5 m $s^{-1}$, $p = 0.03$, MDiff = 8.2%) and DS (3.2 ± 0.2 v 2.6 ± 0.3 m $s^{-1}$, $p = 0.03$, MDiff = 22%) were higher (**Figure 2** – left panel). Although KDP was employed by only three athletes during the Sprint, for all three the velocity with this sub-technique was higher than the average for the Distance event (4.5 ± 0.2 v 3.9 ± 0.5 m $s^{-1}$, $p = 0.25$ MDiff = 12%). Tuck velocity was slightly lower overall during the Sprint (9.1 ± 0.3 v 9.5 ± 0.3 m $s^{-1}$ $p = 0.03$, MDiff = −4%). In contrast to observations on the entire course, the mean velocity for Turn on the common terrain was similar for both events. Minimum and maximum velocities for each of the sub-techniques are presented in **Table 4**.

During the Sprint, mean cycle lengths were shorter with DP (5.5 ± 0.4 v 6.0 ± 0.4 m, $p = 0.06$, MDiff = −9%), but longer for DS (2.5 ± 0.1 v 2.2 ± 0.2 m, $p = 0.06$, MDiff = 10%) and KDP (5.3 ± 0.44 v 5.0 ± 0.4 m, $p = 0.25$, MDiff = 5%) (**Figure 2** – center panel).

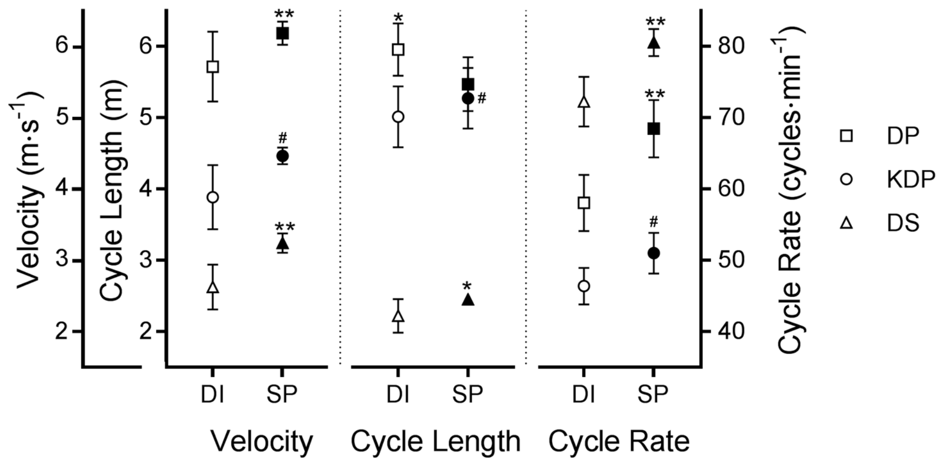


**FIGURE 3 |** Mean velocities, cycle lengths and cycle rates (±SD) with the various sub-techniques on the 1.0-km of common terrain. Open symbols, Distance; closed symbols, Sprint; DP, double pole; KDP, kick-double pole; DS, diagonal stride. Note that KDP was used by only 3 participants in the Sprint event. **$p$ = 0.03 in comparison to the other event, *$p$ = 0.06 in comparison to the other event. #Higher mean value but no statistical significance since only 3 Sprint skiers used KDP.

**TABLE 4 |** Mean, minimum and maximum velocities (±SD) for the various sub-techniques on the 1.0-km of common terrain.

| | Distance Velocity ($m \cdot s^{-1}$) | | | Sprint Velocity ($m \cdot s^{-1}$) | | |
|---|---|---|---|---|---|---|
| **Technique** | **Mean** | **Min** | **Max** | **Mean** | **Min** | **Max** |
| Tuck | 9.3 ± 0.5 | 9.0 ± 0.8 | 9.5 ± 0.3 | 8.9 ± 0.6* | 8.6 ± 1.1 | 9.3 ± 0.2 |
| DP | 5.7 ± 0.5 | 3.6 ± 0.7 | 8.2 ± 0.6 | 6.2 ± 0.2* | 4.2 ± 0.4 | 8.6 ± 0.4 |
| KDP# | 3.9 ± 0.5 | 3.6 ± 0.4 | 4.3 ± 0.7 | 4.5 ± 0.2* | 4.2 ± 0.4 | 4.7 ± 0.4 |
| DS | 2.6 ± 0.3 | 1.7 ± 0.3 | 4.0 ± 0.3 | 3.2 ± 0.2* | 2.1 ± 0.2 | 4.6 ± 0.6 |

*DP, double pole; KDP, kick-double pole; DS, diagonal stride. *$p$ = 0.03 compared to the other event, #KDP was used by only 3 participants in the 1.1-km event.*

All sub-technique mean cycle rates were higher in the Sprint (DP 68.5 ± 4.7 v 58.0 ± 4.2 cycles/min, $p$ = 0.03, MDiff = 16%; DS 80.6 ± 2.8 v 72.3 ± 3.6 cycles/min, $p$ = 0.03, MDiff = 11%; KDP 50.7 ± 3.1 v 46.9 ± 3.1 cycles/min, $p$ = 0.5, MDiff = 8%) (**Figure 2** – right panel).

## DISCUSSION

### Overview

This is the first study of the macro-kinematics of elite female athletes during an entire on-snow competition, and also the first comparison of macro-kinematic parameters between Sprint and Distance cross-country skiing events. In terms of distance, DP was the sub-technique used most extensively in both events, followed by Tuck, DS, Turn, and KDP. KDP was employed relatively little, and during the Sprint event by only half the participants. When events were compared over common terrain we observed that mean race velocities were higher in the Sprint. Mean sub-technique velocities with KDP and DS on the common terrain were higher in the Sprint due to faster cycle rates and longer cycle lengths, while the DP velocity was higher despite a shorter cycle length. During the Sprint the percentage of total distance covered with DP was greater, with the use of Tuck lower and the percentage of both KDP and DS similar relative to the Distance event.

### Common Terrain Macro-Kinematics

On the common terrain both the overall velocity and velocities with DP, KDP, and DS were expected to be higher in the shorter Sprint event. Corresponding elevations in cycle rates were also expected, since on-snow correlations between higher cycle rates and higher velocities for all three of these cyclical classical sub-techniques were reported by Nilsson et al. (2004). While similar correlations have been observed by numerous other investigations, including the study on DP by Lindinger et al. (2009), on KDP with roller-skiing by Göpfert et al. (2013), and on DS on-snow by Andersson et al. (2014), this study confirmed these findings for all sub-techniques throughout an entire on-snow competition. The hypothesis proposed by Zory et al. (2005) to explain this relationship is that a high cycle rate minimizes the decrease in velocity during glide and recovery phases while concurrently reducing the duration of these two phases. Millet et al. (1998) reported that a higher cycle rate would come at a higher metabolic cost, but Zory et al. (2005) noted that this would not be a limiting factor in a Sprint event.

We speculated that the shorter mean DP cycle lengths in the Sprint could be due to usage of DP on steeper inclines before transition to KDP or DS. However, the similar usage of DS in terms of distance, as well as closer examination of where sub-techniques were used around the course, indicated that this was not the case. On sections where DP was used for both events, higher cycle rate in combination with shorter cycles were clearly used to generate the higher DP velocity in the Sprint. This decrease in cycle length with increasing velocity was also observed by Nilsson et al. (2004) on-snow for all cyclical sub-techniques when speeds progressed from "fast" to "maximum," but with DP the cycle lengths decreased earlier, when progressing from "medium" to "fast" velocities.

While this phenomena was also observed with maximal velocities with DS on-snow by Andersson et al. (2014), the velocities in these studies were collected over short sections which may not be indicative of an entire competition. In Nilsson et al.'s (2004) research, the maximal DS and KDP velocities of 6.2 and 6.1 m $s^{-1}$ respectively were collected over 60 m of flat snow; while Andersson et al.'s (2014) DS velocity of 5.6 m $s^{-1}$ was recorded over 50 m up a 7.5° incline. In both instances, the velocities far exceed both the mean and maximal DS and KDP velocities seen here. With other studies also reporting increases in both cycle length and cycle rate with increased velocity at sub-maximal workloads (Vähäsöyrinki et al., 2008; Göpfert et al., 2013), it seems likely then that the highest DS and KDP velocities reached during the Sprint in this study were sub-maximal. In contrast, our mean Sprint DP velocity was comparable to the maximal DP velocity in Nilsson et al.'s (2004) study, (6.2 v 6.3 m $s^{-1}$).

The use of sub-maximal speeds in Sprint competition may reflect pacing, with athletes being unable to maintain maximal velocities over the 1.1-km course, and/or tactically holding back for critical parts of the course. Alternatively, our athletes may not have reached maximal velocity in KDP and DS because of velocity thresholds for sub-technique transitions (**Figure 1**). As athletes attain higher velocities using these two sub-techniques, it becomes possible to change to a faster sub-technique (from DS to KDP, from KDP to DP, and for some, directly from DS to DP). With DP, the velocity threshold for transition to the next fastest technique (Tuck) is too high to be attained on flat terrain, so skiers increase DP velocity by elevating cycle rate at the expense of cycle length. Regardless, this highlights the need for more analysis in the competition environment where sub-techniques are not pre-determined.

### Sub-technique Selection

It is well known that incline also has an effect on sub-technique selection (Sandbakk et al., 2012a; Pellegrini et al., 2013; Ettema et al., 2017). As indicated in **Figure 2**, in terms of distance DS was utilized on the common terrain to a similar extent, approximately 14%, during both Sprint and Distance events. Furthermore, the GPS traces indicate that DS is generally being used on the same course sections in both cases, which would appear to support the conclusion of Ettema et al. (2017) that incline is the primary driver of technique choice. However, it is also possible that the velocity and gradient thresholds for technique transition are passed at the same time, i.e., velocity decreases as gradient rises. Unfortunately, the gradient profile in this present study was not sufficiently detailed to be able to comment further on the effect of gradient on sub-technique transitions. As the slowest sub-technique, the percentage usage of DS in terms of time is much greater (28%) in the Distance event, while due to the faster velocity in the Sprint is only used 25% of the time.

We have observed the low and variable use of KDP previously (Marsland et al., 2017); among the three athletes that used KDP in the Sprint, the average usage in terms of distance was just 2%. In the Distance event, five skiers used KDP over less than 1% of the distance, while the sixth used it for 6%. The mean minimum and maximum velocities in **Table 4** clearly reveal that the minimum DP velocity and the maximum DS velocity overlap, with the range of KDP velocities falling within those of the other two sub-techniques. Some skiers may feel they are more efficient when using one sub-technique compared to another and the choice appears to reflect personal preference.

While DP is the dominant technique during the Sprint, being used on average to cover 50% of the distance, it is also known that on Sprint courses with relatively little climb or, in particular, in fast conditions, skiers race without wax and use DP as their only cyclical technique (in addition to Tuck and Turn). While this happens more frequently in men's classic Sprints [and sometimes with Distance races (FIS, 2015)], women have been known to DP races without wax as well. Interestingly, in the current case it appears that the increased usage of DP in the Sprint (7% more in terms of distance) reflects primarily less usage of Tuck (−3%) and Misc (−4%) sub-techniques. This lower use of Tuck in the Sprint appears to be due to athletes transitioning earlier to DP, particularly going into the finish straight. However, the more extensive usage of irregular technique in the Distance event remains unexplained. A proportion of Misc is made up of the transitions between sub-techniques, however, the number of transitions and Misc velocities in both events were found to be similar.

## Limitations

### Influence of Topography

A key component of our study design was comparing skier macro-kinematics on common terrain under the same conditions. Our observations on the full 10.5-km event highlight the influence of terrain and the challenges involved in comparing between different courses, even when the conditions are similar. For example, the lower Tuck velocities on the remaining 3.5-km loop compared to the analyzed 1.0-km section indicate that the Sprint downhill sections were steeper, as supported by the homologation data (average downhill gradients of 9% during the Sprint race and 6% during the 3.5-km Distance loops). Furthermore, the slower velocities and shorter and more rapid cycle lengths when utilizing DS on the Sprint course are consistent with steeper inclines (average uphill gradients of 12% during the Sprint versus 10% for the 3.5-km loop). A similar observation concerning the relationship between gradient and macro-kinematics while performing DS on rollerskis was reported earlier by Sandbakk et al. (2012a).

Considering technique usage, DP was utilized to a larger extent on the full 10.5-km course (49% of the distance compared to 43% on the 1.0-km section), while the slower DS was employed less extensively (10% compared to 14%). In general, coaches experience that a course with more moderate gradients on uphills promotes greater proportional usage of DP and less DS (as seen here), and, consequently, a higher mean velocity. The outcomes observed here provide a suitable explanation for why the 10.5-km and 1.1-km events had similar overall mean velocities.

Accordingly, care must be taken when comparing macro-kinematics from different courses. For example, the mean overall velocity for the 10.5-km event observed here (5.5 m $s^{-1}$) was similar to the 5.4 m $s^{-1}$ we observed in an earlier men's classic

10-km competition (Marsland et al., 2017). Although the sub-technique velocities in this previous investigation (DP 5.7 m $s^{-1}$, DS 3.4 m $s^{-1}$, KDP 4.4 m $s^{-1}$) were similar to the current study, in the earlier work these velocities were achieved utilizing longer cycle lengths and slower cycle rates. To what extent this difference can be attributed to gender, course topography, snow speed and/or other factors is unknown.

It is worth noting that different macro-kinematic combinations by our skiers were successful. Similar sub-technique velocities were achieved using different proportions of higher cycle lengths and lower cycle rates and vice versa. With our small participant numbers, no macro-kinematic trends could be associated with faster or slower skiers, however, it seems likely that different strategies may be better suited to the strengths and weaknesses of the individual skier.

### Implications and Future Directions

For coaches and athletes there are three main practical applications that are confirmed from this study. First, the macro-kinematic strategies when training for Sprint and Distance events should not be the same. Clearly, the ability to attain higher cycle rates across all sub-techniques is essential for Sprint performance. Secondly, the demands of competition with respect to the different sub-techniques depend to a great extent on the terrain, with different courses requiring a different emphasis. Finally, evaluation of the macro-kinematic characteristics of an individual athlete during both training and competition can provide information concerning relative strengths and weaknesses that can help improve performance. Future studies in this area, involving more participants, should examine macro-kinematic trends of the best athletes in different events, at the same time considering variations in this respect during an event. In addition, assessment of potential gender-related differences over entire courses should provide valuable novel insights.

## CONCLUSION

Cross-country skiers can increase velocity by elevating cadence, increasing power (reflected in longer cycle lengths), and/or changing to a faster sub-technique. By monitoring macro-kinematics continuously throughout Sprint and Distance competitions on the same terrain we were able here to examine how these three mechanisms interact. Differences in the macro-kinematic characteristics and strategies utilized between Sprint and Distance events were confirmed, while at the same time the challenges of comparing between courses with different topographies and evaluating different factors influencing sub-technique selection were highlighted. Further insights are likely to be gained from examining differences in the macro-kinematic strategies of individuals within each event, and by continuing to analyze additional in-competition data.

## AUTHOR CONTRIBUTIONS

FM, JA, GW, and DC: designed the study. FM: collected, processed, and analyzed the data. FM, JA, GW, H-CH, and DC: interpreted the results and wrote the paper.

## ACKNOWLEDGMENTS

Sincere thanks to members of the US Ski Team and Australian Cross Country Ski Team who participated in this study.

## REFERENCES

Andersson, E., Pellegrini, B., Sandbakk, Ø., Stöggl, T., and Holmberg, H. C. (2014). The effects of skiing velocity on mechanical aspects of diagonal cross-country skiing. *Sports Biomech.* 13, 267–284. doi: 10.1080/14763141.2014.921236

Andersson, E., Supej, M., Sandbakk, Ø., Sperlich, B., Stöggl, T., and Holmberg, H. C. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur. J. Appl. Physiol.* 110, 585–595. doi: 10.1007/s00421-010-1535-2

Bilodeau, B., Rundell, K. W., Roy, B., and Boulay, M. R. (1996). Kinematics of cross-country ski racing. *Med. Sci. Sports Exerc.* 28, 128–138. doi: 10.1097/00005768-199601000-00024

Bolger, C. M., Kocbach, J., Hegge, A. M., and Sandbakk, Ø. (2015). Speed and heart-rate profiles in skating and classical cross-country-skiing competitions. *Int. J. Sports Physiol. Perform.* 10, 873–880. doi: 10.1123/ijspp.2014-0335

Ettema, G., Kveli, E., Øksnes, M., and Sandbakk, Ø. (2017). The role of speed and incline in the spontaneous choice of technique in classical roller-skiing. *Hum. Mov. Sci.* 55, 100–107. doi: 10.1016/j.humov.2017.08.004

FIS (2015). *Poltoranin Wins Stage 4 of Tour de Ski in Toblach*. Available at: http://www.fis-ski.com/cross-country/news-multimedia/news/article=poltoranin-wins-stage-tour-ski-toblach.html [accessed on January 11, 2018].

FIS (2017). *Cross-Country Calendar*. Available at: https://data.fis-ski.com/cross-country/calendar.html [accessed on October 24, 2017].

FIS (2018). *The International Competition Rules (ICR) Cross-Country*. Available at: http://www.fis-ski.com/inside-fis/document-library/cross-country/index.html#deeplink=rules [accessed on March 9, 2018].

Göpfert, C., Holmberg, H. C., Stöggl, T., Müller, E., and Lindinger, S. J. (2013). Biomechanical characteristics and speed adaptation during kick double poling on roller skis in elite cross-country skiers. *Sports Biomech.* 12, 154–174. doi: 10.1080/14763141.2012.749939

Harding, J. W., Mackintosh, C. G., Hahn, A. G., and James, D. A. (2008). *Classification of Aerial Acrobatics in Elite Half-Pipe Snowboarding Using Body Mounted Inertial Sensors (P237) The Engineering of Sport 7*. Paris: Springer, 447–456.

Lindinger, S. J., Stöggl, T., Müller, E., and Holmberg, H. C. (2009). Control of speed during the double poling technique performed by elite cross-country skiers. *Med. Sci. Sports Exerc.* 41, 210–220. doi: 10.1249/MSS.0b013e318184f436

Marsland, F., Lyons, K., Anson, J., Waddington, G., Macintosh, C., and Chapman, D. (2012). Identification of cross-country skiing movement patterns using micro-sensors. *Sensors* 12, 5047–5066. doi: 10.3390/s120405047

Marsland, F., Mackintosh, C., Anson, J., Lyons, K., Waddington, G., and Chapman, D. (2015). Using micro-sensor data to quantify macro kinematics of classical cross-country skiing during on-snow training. *Sports Biomech.* 14, 435–447. doi: 10.1080/14763141.2015.1084033

Marsland, F., Mackintosh, C., Holmberg, H.-C., Anson, J., Waddington, G., Lyons, K., et al. (2017). Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. *PLoS One* 12:e0182262. doi: 10.1371/journal.pone.0182262

Mikkola, J., Laaksonen, M. S., Holmberg, H. C., Nummela, A., and Linnamo, V. (2013). Changes in performance and poling kinetics during cross-country sprint skiing competition using the double-poling technique. *Sports Biomech.* 12, 355–364. doi: 10.1080/14763141.2013.784798

Millet, G. Y., Hoffman, M. D., Candau, R. B., Buckwalter, J. B., and Clifford, P. S. (1998). Cycle rate variations in roller ski skating: effects on oxygen uptake and poling forces. *Int. J. Sports Med.* 19, 521–525. doi: 10.1055/s-2007-971954

Myklebust, H., Nunes, N., Hallen, J., and Gamboa, H. (2011). Morphological analysis of acceleration signals in cross-country skiing – information extraction and technique transitions detection. *Paper Presented at the International Conference on Bio-inspired Systems and Signal Processing*, Rome.

Nilsson, J., Tveit, P., and Eikrehagen, O. (2004). Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech.* 3, 85–107. doi: 10.1080/14763140408522832

Pellegrini, B., Zoppirolli, C., Bortolan, L., Holmberg, H. C., Zamparo, P., and Schena, F. (2013). Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Hum. Mov. Sci.* 32, 1415–1429. doi: 10.1016/j.humov.2013.07.010

Rindal, O. M. H., Seeberg, T. M., Tjonnas, J., Haugnes, P., and Sandbakk, Ø. (2017). Automatic classification of sub-techniques in classical cross-country skiing using a machine learning algorithm on micro-sensor data. *Sensors* 18:E75. doi: 10.3390/s18010075

Sakurai, Y., Fujita, Z., and Ishige, Y. (2014). Automated identification and evaluation of subtechniques in classical-style roller skiing. *J. Sports Sci. Med.* 13, 651–657.

Sakurai, Y., Fujita, Z., and Ishige, Y. (2016). Automatic identification of subtechniques in skating-style roller skiing using inertial sensors. *Sensors* 16:E473. doi: 10.3390/s16040473

Sandbakk, Ø., Ettema, G., and Holmberg, H. C. (2012a). The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. *Eur. J. Appl. Physiol.* 112, 2829–2838. doi: 10.1007/s00421-011-2261-0

Sandbakk, Ø., Ettema, G., Leirdal, S., and Holmberg, H. C. (2012b). Gender differences in the physiological responses and kinematic behaviour of elite sprint cross-country skiers. *Eur. J. Appl. Physiol.* 112, 1087–1094. doi: 10.1007/s00421-011-2063-4

Sandbakk, Ø., Ettema, G., Leirdal, S., Jakobsen, V., and Holmberg, H. C. (2011). Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur. J. Appl. Physiol.* 111, 947–957. doi: 10.1007/s00421-010-1719-9

Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sandbakk, Ø., Holmberg, H. C., Leirdal, S., and Ettema, G. (2010). The physiology of world-class sprint skiers. *Scand. J. Med. Sci. Sports* 21, e9–e16. doi: 10.1111/j.1600-0838.2010.01117.x

Sandbakk, Ø., Losnegard, T., Skattebo, Ø., Hegge, A. M., Tønnessen, E., and Kocbach, J. (2016). Analysis of classical time-trial performance and technique-specific physiological determinants in elite female cross-country skiers. *Front. Physiol.* 7:326. doi: 10.3389/fphys.2016.00326

Seeberg, T. M., Tjønnås, J., Rindal, O. M. H., Haugnes, P., Dalgard, S., and Sandbakk, Ø. (2017). A multi-sensor system for automatic analysis of classical cross-country skiing techniques. *Sports Eng.* 20, 313–327. doi: 10.1007/s12283-017-0252-z

Smith, G. A., and Heagy, B. S. (1994). Kinematic analysis of skating technique of Olympic skiers in the men's 50-km race. *J. Appl. Biomech.* 10, 79–79. doi: 10.1123/jab.10.1.79

Stöggl, T., Holst, A., Jonasson, A., Andersson, E., Wunsch, T., Norström, C., et al. (2014). Automatic classification of the sub-techniques (gears) used in cross-country ski skating employing a mobile phone. *Sensors* 14, 20589–20601. doi: 10.3390/s141120589

Stöggl, T., Lindinger, S., and Müller, E. (2007). Analysis of a simulated sprint competition in classical cross country skiing. *Scand. J. Med. Sci. Sports* 17, 362–372.

Vähäsöyrinki, P., Komi, P. V., Seppala, S., Ishikawa, M., Kolehmainen, V., Salmi, J. A., et al. (2008). Effect of skiing speed on ski and pole forces in cross-country skiing. *Med. Sci. Sports Exerc.* 40, 1111–1116. doi: 10.1249/MSS.0b013e3181666a88

Vesterinen, V., Mikkola, J., Nummela, A., Hynynen, E., and Häkkinen, K. (2009). Fatigue in a simulated cross-country skiing sprint competition. *J. Sports Sci.* 27, 1069–1077. doi: 10.1080/02640410903081860

Wagner, W., and Horel, J. (2011). Observations and simulations of snow surface temperature on cross-country ski racing courses. *Cold Reg. Sci. Technol.* 66, 1–11. doi: 10.1016/j.coldregions.2010.12.003

Zory, R., Barberis, M., Rouard, A., and Schena, F. (2005). Kinematics of sprint cross-country skiing. *Acta Bioeng. Biomech.* 7, 87–96.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 25 July 2018
doi: 10.3389/fphys.2018.00978

# Following a Long-Distance Classical Race the Whole-Body Kinematics of Double Poling by Elite Cross-Country Skiers Are Altered

*Chiara Zoppirolli[1,2]*, Lorenzo Bortolan[1,2], Federico Stella[1,2], Gennaro Boccia[3], Hans-Christer Holmberg[4,5], Federico Schena[1,2] and Barbara Pellegrini[1,2]*

[1] CeRiSM (Research Center Sport Mountain and Health), Rovereto, Italy, [2] Department of Neuroscience, Biomedicine and Movement, University of Verona, Verona, Italy, [3] NeuroMuscularFunction Research Group, Department of Medical Sciences, School of Exercise and Sport Sciences, University of Turin, Turin, Italy, [4] Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Östersund, Sweden, [5] School of Sport Sciences, UiT The Arctic University of Norway, Tromsø, Norway

**Introduction:** Although short-term (approximately 10-min) fatiguing DP has been reported not to alter the joint kinematics or displacement of the centre of mass (COM) of high-level skiers, we hypothesize that prolonged DP does change these kinematics, since muscular strength is impaired following endurance events lasting longer than 2 h.

**Methods:** During the 58-km Marcialonga race in 2017, the fastest 15 male skiers were videofilmed (100 fps, FHD resolution in the sagittal plane) on two 20-m sections (inclines: 0.7 ± 0.1°) 48 km apart (i.e., 7 and 55 km from the start), approximating 50- km Olympic races. The cameras were positioned perpendicular to and about 40 m from the middle of each section and spatial dimensions adjusted for each individual track skied. Pole and joint kinematics, as well as displacement of the COM during two DP cycles were assessed.

**Results:** The 10 skiers who fulfilled our inclusion criteria finished the race in 2 h 09 min 19 s ± 28 s. Displacements of the joints and COM were comparable to previous observations on skiers roller skiing on a flat treadmill at similar speeds in the laboratory. 55 km after the start, cycle velocity and length were lower ($P < 0.001$ and $P = 0.002$, respectively) and the angular range of elbow joint flexion during the initial part of the poling phase reduced, while shoulder angle was greater during the first 35% of the DP cycle (all $P < 0.05$). Moreover, the ankle angle was increased and forward displacement of the COM reduced during the first 80% of the cycle.

**Conclusion:** Prolonged DP reduced the forward displacement of the COM and altered arm kinematics during the early poling phase. The inefficient utilization of COM observed after 2 h of competition together with potential impairment of the stretch-shortening of arm extensor muscles probably attenuated generation of poling force. To minimize these effects of fatigue, elite skiers should focus on maintaining optimal elbow and ankle kinematics and an effective forward lean during the propulsive phase of DP.

**Keywords: whole-body kinematics, fatigue, marathon, cross-country skiing, centre of mass, stretch-shortening cycle**

OPEN ACCESS

***Edited by:***
*Gregoire P. Millet, Université de Lausanne, Switzerland*

***Reviewed by:***
*Raphael Faiss, Université de Lausanne, Switzerland*
*Fiorenzo Moscatelli, University of Foggia, Italy*

****Correspondence:***
*Chiara Zoppirolli*
*chiara.zoppirolli@univr.it*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *26 April 2018*
***Accepted:*** *03 July 2018*
***Published:*** *25 July 2018*

***Citation:***
*Zoppirolli C, Bortolan L, Stella F, Boccia G, Holmberg H-C, Schena F and Pellegrini B (2018) Following a Long-Distance Classical Race the Whole-Body Kinematics of Double Poling by Elite Cross-Country Skiers Are Altered. Front. Physiol. 9:978. doi: 10.3389/fphys.2018.00978*

## INTRODUCTION

Technical skills are extremely important to the success of elite cross-country skiers and, consequently, constitute an integral part of their training schedule. Sport-specific activities, such us skiing, roller skiing, and training movement-specific maximal strength, power, core stability and motor control, are key elements of training by world-class cross-country skiers (Sandbakk et al., 2011; Sandbakk and Holmberg, 2014). Indeed, the production of propulsive force is determined not only by muscular strength, but also by the kinematics with which each specific technique is performed. For example, rapid propulsive action with proper timing of force application is related to high-level performance with several cross-country skiing techniques (Stöggl and Müller, 2009; Stöggl et al., 2010). In addition, elevation and forward positioning of the centre of mass (COM) during the beginning of the poling phase of double poling leads to greater propulsive force (Zoppirolli et al., 2015).

Fatigue might alter the kinematics of cross-country skiing, either directly by changing the coordination of movements and/or indirectly by reducing muscle force. A limited number of studies have examined the effects of short-term fatiguing skiing exercises on the whole-body kinematics of double poling, but to our knowledge none have focused on the relationship between fatigue and the whole-body kinematics associated with other cross-country skiing techniques. Between the final spurts of successive bouts of a simulated classical sprint race on-snow, Zory and colleagues observed slight modifications in the joint angular displacement of high-level cross-country skiers while double poling (Zory et al., 2009). Hip flexion was less during the poling phase and hip extension lower at the end of the recovery phase, leading to the hypothesis that fatigue reduces both the contribution of the trunk to propulsion and the effectiveness of the preparation phase. In contrast, our research group found no significant differences in the displacement of joints and the COM while double poling at the same sub-maximal intensity before and after short-term high-intensity fatiguing exercise (Zoppirolli et al., 2016). We therefore proposed that the reduction in the poling force observed in high-level cross-country skiers is due to neuromuscular fatigue rather than any alteration in whole-body kinematics.

Apparently, no investigations on the effects of prolonged cross-country skiing on whole-body kinematics have been performed. However, the influence of neuromuscular fatigue following cross-country skiing marathons on motor drive and/or excitation-contraction coupling has been examined. Millet and Lepers (2004) demonstrated that after such a skating marathon neuromuscular fatigue in knee extensor muscles is primarily of peripheral origin. Boccia's research group observed both central and peripheral fatigue after a classical cross-country skiing marathon (Boccia et al., 2016). Although the central fatigue in elbow and knee extensor muscles was similar, peripheral fatigue was more pronounced in the former, a difference attributed to the repetitive stretch-shortening of these muscles during double poling (Nicol et al., 2006), as well as to the extensive acidosis likely to be present in upper-limb muscles exercising at high intensity due to the different muscle fiber compositions. Other investigators found that peripheral fatigue is the primary cause of loss of strength and poorer performance following high-intensity cross-country skiing of short duration (Zory et al., 2006, 2011; Zoppirolli et al., 2016).

The aim of the current study was to evaluate the effects of a long-distance classical cross-country skiing race on whole-body kinematics and cycle timing during double poling. For this purpose, the 2-D displacements of joints and the COM of elite cross-country skiers at the beginning and end of a 58-km classical marathon (during which only double poling was used) were determined. Our hypothesis, based primarily on the reduction in muscular strength known to be caused by prolonged cross-country skiing, was that double poling for longer than 2 h reduces both cycle velocity and length, together with alterations in whole-body kinematics, primarily with respect to the displacement of upper-body joints and COM positioning during the poling phase.

## MATERIALS AND METHODS

### Competition and Experimental Section

The double-poling kinematics of elite skiers who participated in the 44th Marcialonga ski marathon (2017), a classical cross-country ski race held annually in Val di Fiemme (Italy) as part of the FIS ski marathon circuit, were analyzed. The course is usually approximately 70 km in length, but was reduced to 58 km that year due to lack of snow. The course was mainly flat and double poling was the only technique used by the first 50 athletes who finished first. Several weeks before this competition, we inspected the first and last parts of the course for suitable sections for filming. Straight 20-m sections with an incline of $<1°$ and located 7 and 55 km from the starting line were selected. The approximately 48-km distance between these two sections is close to the length of a 50-km Olympic race.

### The Skiers

We analyzed the video recordings of all 50 skiers who crossed the two sections selected first, to ensure inclusion of the first 15 who finished first overall. The identities of the first 10 out of the 15 skiers who met the inclusion criteria described below were unknown to us during the analysis. The general characteristics of these skiers (age, height, weight and FIS points) are presented in the Results.

### Filming

Prior to the race, a full high-definition camera (FZ 200 LUMIX, Panasonic Corp., Osaka, Japan) was positioned perpendicularly to each section to be filmed, approximately 40 m from its midpoint and level relative to the horizontal line. This set-up, in combination with recording at 100 fps and maximal zooming in on the 20 m of interest, were chosen to minimize image distortion in the sagittal plane. In addition, another camera (GoPro Hero, GoPro Inc., San Mateo, CA United States) was positioned, at the beginning of and pointing toward the central portion of each section, to allow recognition of each skier and the track he skied.

## Space Calibration and Environmental Measurements

To ensure that the kinematic analysis was as accurate as possible, both filming sections were calibrated carefully before the skiers arrived. The horizontal leveling was checked with a custom-made liquid-level system. Five cones with a tennis ball on top were positioned equal distances apart alongside the three parallel track in each section (**Figure 1**). Thereafter, a short calibration video was recorded. This set-up allowed determination of spatial parameters for each individual track. Everything except the system for assuring the horizontal level was removed following this calibration.

The air and snow temperatures and atmospheric humidity at both sections were measured before the skiers arrived. The weather was sunny, with no wind, and on the first and second sections the snow temperature was −18° and −5°, respectively; the air temperature −10° and +1° and humidity 68 and 68%, respectively. Moreover, snow-ski friction was assessed on the basis of the deceleration (measured employing a photocell with 1-ms resolution) of a skier (not involved in the competition) after accelerating by double poling and then gliding on the track in a crunch position. This skier passed four gates 1, 4 and 1 m apart and deceleration was calculated as the difference in velocity from gate 1 to 2 and from gate 3 to 4, divided by the time required to move from gate 2 to 4. This test was performed on each section by two skiers, both weighing 70 kg and with skis prepared in the same manner. The mean values from three consecutive trials was used to calculate deceleration. Thereafter, snow-ski friction was calculated according to Budde, assuming friction to be the only force acting against the skier's movement (i.e., neglecting air drag), utilizing the formula:

$$\mu = a \cdot (g \cdot cos\alpha)^{-1},$$

where $\mu$ is the snow-ski friction coefficient, $a$ deceleration, $g$ gravitational acceleration and $\alpha$ the incline of the track (Budde and Himes, 2017). We are aware that ski wax will be altered by prolonged skiing and that measurement of ski friction with skies that had been used for approximately 50 km would have provided a more realistic estimate of the snow-ski friction during the second session. However, this was not possible for practical reasons, i.e., the same track could not be skied immediately before the race and there was no other way to accurately reproduce the alterations in the ski wax.

## Inclusion Criteria and Tracking Procedures

Of the 15 male skiers who finished first, we analyzed the first 10 who (a) were completely visible for the entire length of both filming zones (i.e., not obscured by other skiers), (b) completed two DP cycles within each 20-m section, (c) did not change the track or (d) look back (e.g., at opponents) during the filming, and (e) had a cycle velocity on both sections within 2 $km \cdot h^{-1}$ of the mean value for the entire group.

All videos recordings and calibration photograms were processed with the *Tracker* software (Tracker 4.11.0 Copyright© 2017 Douglas Brown)[1]. A 20-m calibration space was defined by a line joining the centers of the tennis balls on top of the first and last cones (**Figure 2**), with a maximal error in the inter-cone distances of 0.05 m (1%), minimizing image distortion. For each track, we defined a bi-dimensional Cartesian plane with its $x$-axis (antero-posterior dimension) parallel to the horizontal plane, $z$-axis (vertical dimension) perpendicular to this same plane and origin at the base of the first cone. The incline of each track was determined as the angle between the $x$-axis and the 20-m calibration line (**Figure 2**). Calibration was performed for each individual track skied, and uploaded on video clips according to the track used by each athletes.

Tracking of each skier was initiated at the time of his first pole plant (PP, i.e., the beginning of the poling phase) after passing the origin of Cartesian plane, and continued until the third PP, i.e., for two complete cycles of double poling. The three PPs and two pole offs (PO, i.e., the end of the poling phase) were identified from the first frame in which the tip of the pole showed no horizontal or vertical movement, or when movement began, respectively. At these time-points both the tip of the pole and another random point near the top of the pole were tracked manually, in order to calculate the pole angle. Semi-automatic tracking (i.e., based on the creation of two recognition zones around the point of interest) was applied to identify the x and z coordinates of the center of rotation of the shoulders, elbows, hips, knees and ankles, as well as the center of the hands and tips of the feet in each frame.

## Parameters and Data Analysis

The horizontal (x) and vertical (z) coordinates of each point, as well as the exact associated time-point, were processed with the MATLAB R2017a software (The MathWorks, Inc., Natick, MA, United States) using a custom-written code. To compensate for the skier's vertical position relative to the origin, the z-coordinate of each point of interest was corrected for any specific x-coordinate with the formula:

$$z_{corr} = z - (x \cdot cos\alpha \cdot sin\alpha)$$

where $\alpha$ was the track incline relative to the $x$-axis. This correction allowed comparison of the joint and COM displacements of all subjects skiing on different tracks in the two sections.

For each skier, cycle duration, length and frequency were calculated on the basis of the mean time that elapsed and distance traveled between consecutive PPs. Poling duration was the mean time between a PP and the next PO, expressed in both seconds and percentage of the cycle time. The mean pole angles at the three PP and two PO were also calculated.

Starting from the x- and z-coordinates of the point monitored, the angles of the shoulder, elbow, hip, knee, and ankle joints in the sagittal plane during the two DP cycles were calculated. In addition, the vertical displacement of the center of mass (zCOM), as well as its antero-posterior displacement (θCOM, calculated as the angle of a line between the medial point of the foot and COM, and the vertical line) were determined as proposed previously

[1] physlets.org/tracker

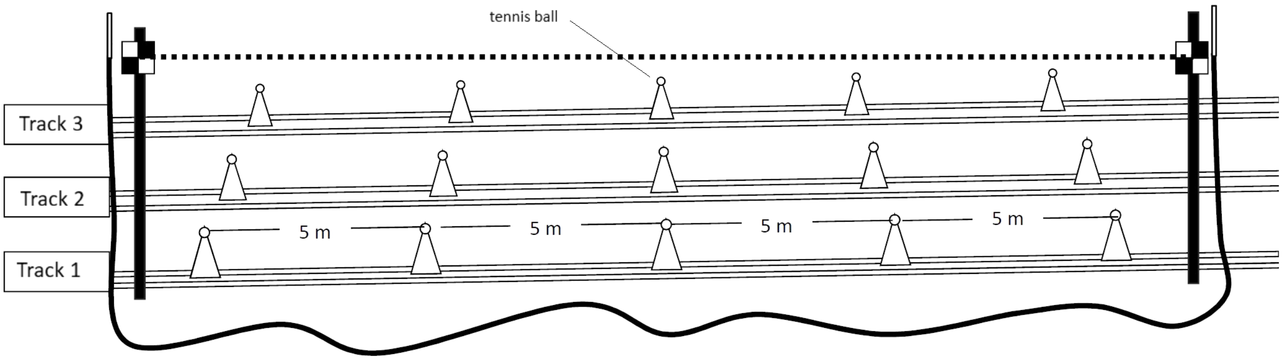


**FIGURE 1 |** Calibration of the tracks. Cones with a tennis ball on top were placed 5 m apart alongside the middle of each track in the 20-m section. Two 2-m poles (black) were planted near the beginning and end of the section, outside the field of competition. A horizontal line was drawn between the black-and-white reference squares on these poles, ensuring levelness with a custom-made system (a long tube of soft plastic 1 cm in diameter and filled to 80% with alcohol). This calibration was necessary to determine the spatial dimensions of each track skied.

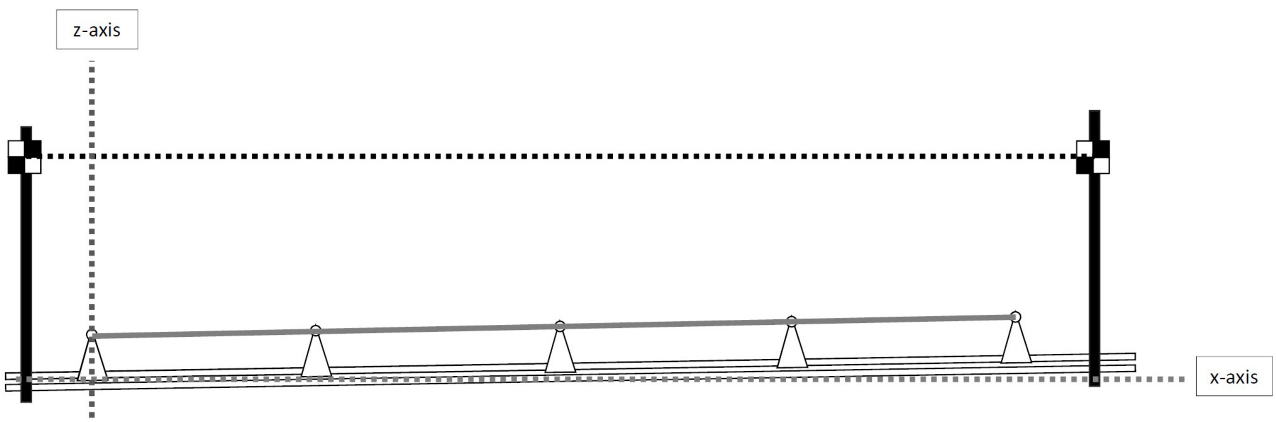


**FIGURE 2 |** Calibration of each track with the *Tracker* software. The solid gray line joining the center of the tennis balls on the top of the outermost cones was used for calibration (20 m long, in the real situation). The dashed gray lines indicate the bi-dimensional Cartesian plane. The *x*-axis was a line parallel to the horizontal plane (dashed black line). The *z*-axis, perpendicular to the *x*-axis, was provided automatically by the software. The origin of the Cartesian plane was positioned at the base of the first cone. The incline of the track was the incline of the calibration tool relative to the *x*-axis.

(Zoppirolli et al., 2015). All of the data for each cycle were re-sampled at 100 points. Joint and COM displacement data of the two cycles were overwritten in order to control for accuracy and repeatability as well as to compute a mean cycle for each athlete (**Figure 3**).

## Statistical Analyses

Values are presented as means ± SD. The Shapiro–Wilk test was employed to verify normal distribution of the data concerning cycle time, joint angles and position of the COM at specific time-points in the cycle (i.e., PP and PO). The *Student t-test* was used to evaluate potential differences in these parameters between the two sections (these results are presented in **Tables 2**, **3**). Moreover, a more detailed statistical approach was employed to compare joint and COM displacement on the two sections: a two-way ANOVA for repeated measures was performed for each 5% time segment of the cycle, thereby providing a measure of significance for 20 equal segments within the cycle (results presented in **Figures 4**, **5**). The IBM SPSS Statistics 22 software (IBM Corp., Armonk, NY, United States) was utilized for these statistical analyses and a *P-value* of less than 0.05 considered statistically significant.

# RESULTS

The 10 skiers who fulfilled the criteria for inclusion (whose anthropometric and performance characteristics are described in **Table 1**) finished the 58-km race within 1 min 18 s after the winner, who finished in 2 h 8 min 36 s. The cycle velocity declined from 24.3 ± 0.9 km·h$^{-1}$ on the first section to 22.5 ± 0.8 km·h$^{-1}$ on the second ($P < 0.001$, **Table 2**), even though the snow-ski friction coefficient decreased (from 0.054 ± 0.005 and 0.036 ± 0.004, on the first and second sections, respectively). While the cycle frequency ($P = 0.155$) and angle of the pole at

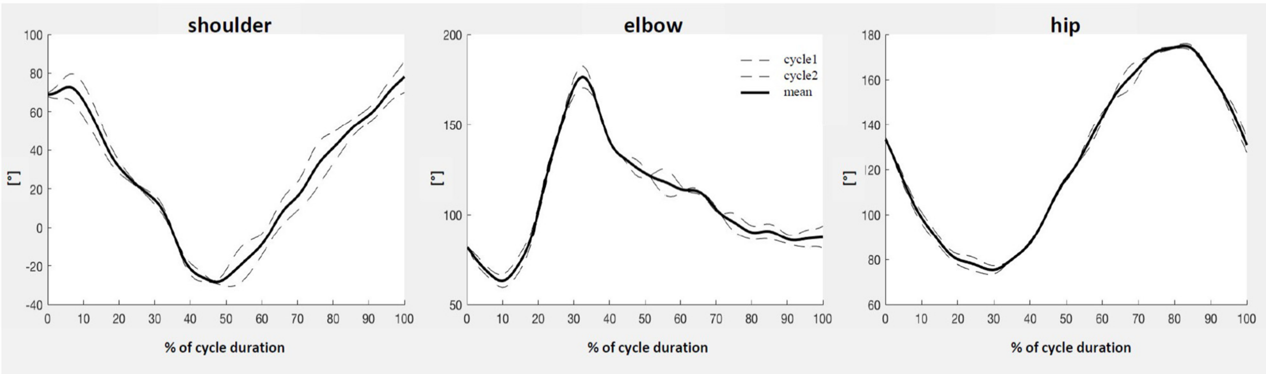


**FIGURE 3 |** Representative analysis of the kinematics of three of the joints examined. Displacement of the joints and COM during each of the two cycles (dashed lines) was re-sampled at 100 points, in order to calculate the mean cycle displacement for each athlete (solid line).

PP and PO remained unaltered, both the cycle velocity (−7.9%, $P < 0.001$) and length (−13.1%, $P = 0.002$) decreased and the duty factor rose (+10.1%, $P = 0.034$) (**Table 2**). However, since cycle velocity was not correlated with the mean, minimal or maximal joint angles or position of the COM at PP or PO, we concluded that variations in cycle velocity were not responsible for eventual differences in whole-body kinematics and, therefore, did not include cycle velocity as a covariate in the statistical analyses.

The kinematic analysis in the sagittal plane revealed that both the absolute values and ranges of motion (ROM) of the hip and knee joints, as well as the *z*COM displacement did not differ between the two sections (all $P > 0.05$) (**Table 2** and **Figure 4**). In contrast, the angles of the shoulders, elbows, and ankle joints and antero-posterior displacement of the COM were dissimilar at some specific points in the DP cycle. Thus, the shoulder joint had a wider angle during the initial 35% of the cycle time ($P < 0.050$) on the second section, but similar angles for the remainder of the cycle ($P > 0.050$) (**Figure 4**). However, the total shoulder ROM remained the same ($P > 0.05$, **Table 2**).

Moreover, although the angle of the elbow joint at PP (**Table 3**) and during the first 5% of the cycle time ($P > 0.05$, **Figure 4**) was similar on both sections this angle was more extended between 5 and 15% of the cycle ($P < 0.050$) on the second section, when the typical local minimum of this angle was higher (**Table 3**). Consequently, the ROM of the elbow joint during flexion was reduced (from 23 ± 7 to 15 ± 8, $P = 0.033$), as was the overall elbow ROM (**Table 2**). Moreover, the elbow joint was also more extended between 65 and 85% of the cycle time (**Figure 4**, $P < 0.050$) on the second section.

Furthermore, on the second section the angle of the ankle joint was wider the initial 80% of the cycle duration ($P < 0.050$), but its total ROM was not different ($P > 0.225$, **Table 2**). Although the vertical displacement of the COM did not change (**Figure 5**), the θCOM was less inclined relative to the vertical for most of the cycle on the second section. Thus, there were significant differences in this respect at 0–10, 20–75%, and 95–100% of the cycle (**Figure 5**, $P < 0.050$) whereas its total ROM was unchanged (**Table 2**).

## DISCUSSION

The present findings show that following 50 km of double poling racing, elite cross-country skiers exhibit (a) reduced skiing velocity, (b) an increase in duty cycle, (c) unaltered cycle frequency, (d) changes in shoulder, elbow and ankle kinematics during certain parts of the cycle, as well as (e) reduced displacement of the COM in the forward direction prior to and during the propulsive phase. At the same time, the kinematics of the hips and knees and vertical displacement of the COM remained similar.

### Double Poling Velocity

The snow-ski coefficient of friction was probably lowered by the higher snow and air temperatures on the second section, a reduction presumably experienced by all of the skiers. This coefficient decreases progressively as the air temperature rises from below (around −10°C) to above zero (around + 5°C), irrespective of ski grinding and waxing. Budde and Himes estimated that when skiing on flat terrain, the time required to ski each kilometer increases by approximately 2 s for every 0.001 increase in the coefficient of friction (Budde and Himes, 2017). Since the snow-ski friction coefficient was 0.014 lower on the second section here, skiing velocity would theoretically have been 19% or 28 s per kilometer faster on the second section, rising from 24 to 30 km·h$^{-1}$ (assuming the same extent of fatigue). However, the skiing velocity actually fell by 8%, or 12 s per kilometer, apparently due to fatigue. Even though the difference in friction coefficient between the two sections filmed might have been overestimated slightly by our methodology, a recent report on a previous Marcialonga race on the same 58-km track supports our proposal that the decrement in speed is due to fatigue, since neuromuscular alterations in both the arms and legs were observed after that competition (Boccia et al., 2016).

The positive pacing strategy adopted by our skiers is common among competitors in many other endurance sports as well (Abbiss and Laursen, 2008). The 8% reduction in skiing velocity observed here is similar to the small decreases demonstrated

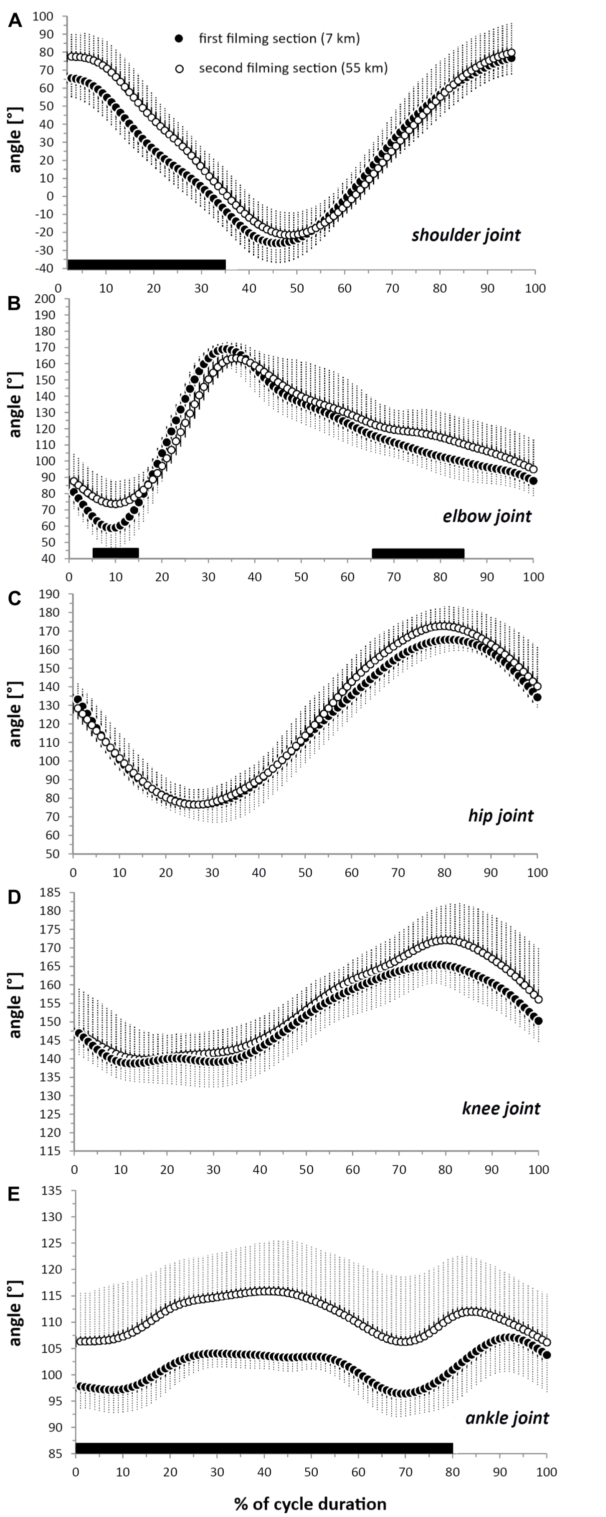


**FIGURE 4 |** Displacement of the shoulder **(A)**, elbow **(B)**, hip **(C)**, knee **(D),** and ankle **(E)** joints during an averaged and time-normalized (100 points) cycle of double poling. The black circles show values on the first section (7 km after the start) and the white circles values on the second section (55 km after the start). The horizontal black bars indicate the portions of the cycle during which the difference between these sections was statistically significant ($P < 0.05$).

previously by elite male cross-country skiers during middle- or long-distance competitions (Carlsson et al., 2016; Losnegard et al., 2016; Welde et al., 2017), as well as with findings on elite runners (Hanley, 2016). This reduction in the second section was due primarily to shorter cycles, since cycle frequency was unaltered.

## Cycle Frequency

The self-selected frequency of movement while, e.g., walking (Bereket, 2005), running (de Ruiter et al., 2014), cycling (Brisswalter et al., 2000), or cross-country skiing (Leirdal et al., 2013) is close to the frequency that minimizes the energetic cost. In particular, Lindinger and Holmberg have shown that double poling at 60 cycles per minute (i.e., 1 Hz, approximately the frequency chosen by our skiers on both sections) is more beneficial in several ways than double poling at 80 or 40 cycles per minute, especially at high velocities (Lindinger and Holmberg, 2011). At 1 Hz, poling force was moderate at all speeds examined (12, 18, and 24 km·h$^{-1}$), with lower oxygen consumption, heart rate and blood lactate values at low and moderate velocities, and even minimal values for these parameters at the highest velocity. These authors proposed that utilization of such a frequency at relatively high velocities guarantees minimal poling times, effective generation of poling force, sufficient recovery time for repositioning the body, and efficient muscle perfusion and removal of lactate, as well as an acceptable level of mechanical work and rhythm of breathing.

The effects of long-lasting exercise of different types on movement frequency are controversial. For example, cycling cadence was reported to decline by approximately 10 rpm when exercise continuoused for longer than 1.5 h (Brisswalter et al., 2000; Hansen and Smith, 2009), whereas stride frequency was maintained or decreased only slightly between the initial and final sections of marathon or ultra-marathon running (Hunter and Smith, 2007; Schena et al., 2014; Giovanelli et al., 2017). Less frequent movements may reflect a shift of the power-velocity curve toward the right: a certain amount of power (needed for body propulsion) is exerted with slower contraction in the fatigued than unfatigued state (Jones and Watt, 1971).

Unfortunately, to our knowledge nothing concerning the effects of cross-country skiing for 1 h or more on choice of cycle frequency by elite athletes has yet been published. Recently, Welde et al. (2017) observed no difference in the frequency of double poling or double poling with kick (around 0.92 Hz) by top-level skiers between the first and last laps on the flat section and intermediate incline of a 15-km classical race. In addition, others have found no significant differences in double poling frequency by elite skiers between the final spurt during the first and last bouts of simulated classical sprint races (Zory et al., 2009; Mikkola et al., 2013; Asan Grasaas et al., 2014). In the case of our investigation, cycle frequency remained unchanged throughout the race, probably because highly skilled athletes strive for this, shifting internally their focus of attention to manage a long-duration effort, in order to optimize performance and perhaps minimize the risk of injury (Morgan and Pollock, 1977; Masters and Ogles, 1998; Tenenbaum, 2001).

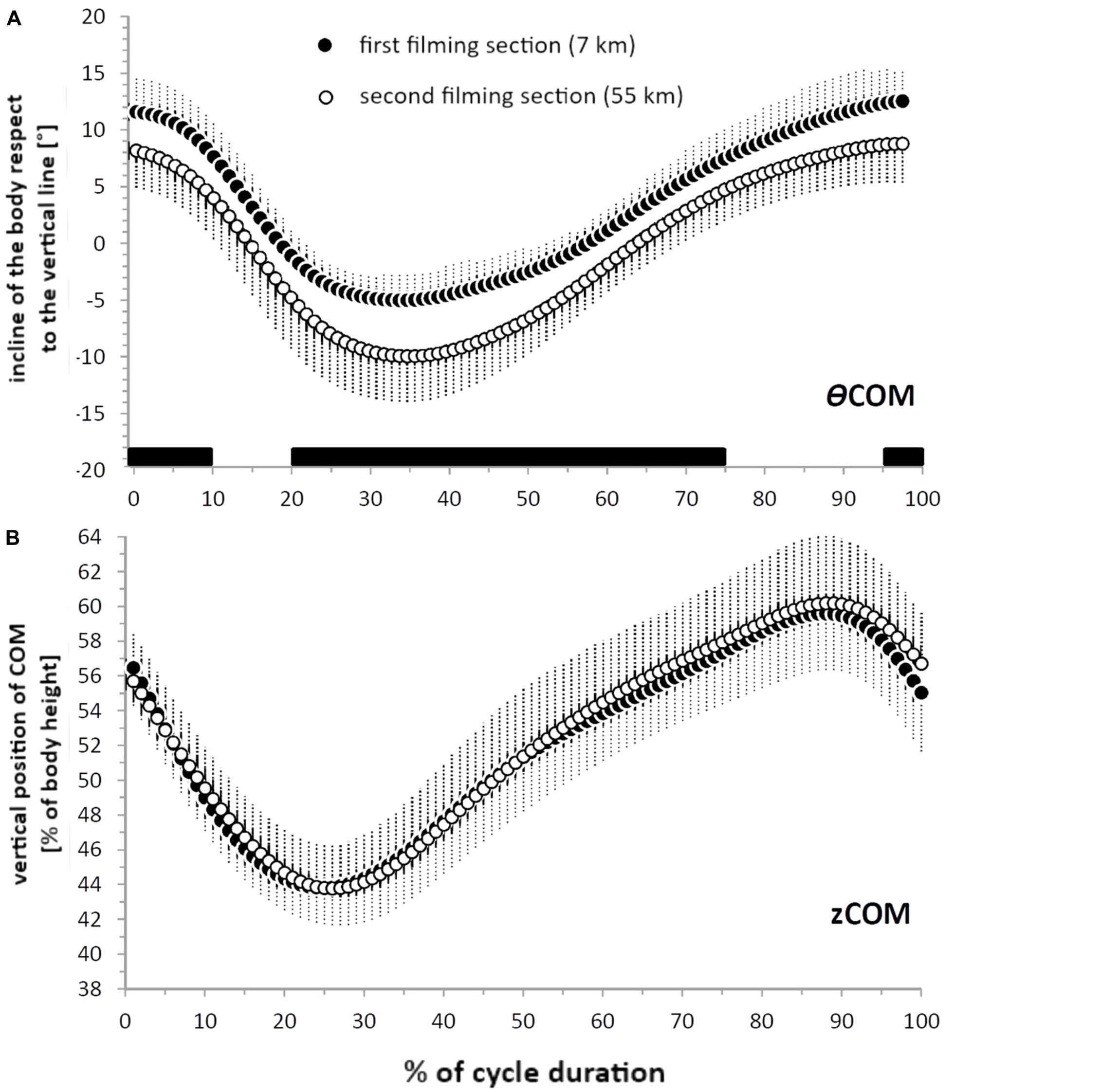


**FIGURE 5 |** Incline of the body respect to the vertical (θCOM) **(A)**, and the vertical position of the centre of mass (zCOM) **(B)** during an averaged and time-normalized (100 points) cycle of double poling. The black circles show values on the first section (7 km after the start) and the white circles values on the second section (55 km after the start). The horizontal black bars indicate the portions of the cycle during which the difference between these sections was statistically significant ($P < 0.05$).

## Displacement of the Joints and COM

While maintaining the same flexion-extension pattern and range of motion, the ankle joint was approximately 10° more extended for much of the cycle on the second section, possibly indicating a more vertical body, with less forward lean. Indeed, on this same section the incline of the θCOM was approximately 4–5° less during the first 10% of the poling phase, most of the recovery phase and the final 5% of the cycle. This finding highlights once again the importance of the forward lean of the body to exploit gravitational forces during the first part of the poling phase, when peak poling force is attained (Zoppirolli et al., 2015). With double poling, activation of the hip and trunk flexors is higher at faster than slower speeds and also begins significantly earlier in relationship to pole plant, stiffening the core muscles to enable skiers to pole powerfully (Zoppirolli et al., 2017). Here, we demonstrate that prolonged double poling at elevated speed limits the ability to maintain a forward-leaning body during the poling phase, perhaps due to reductions in the strength of the core and abdominal muscles. Accordingly, we propose that the kinematic changes observed in the ankle joint and θCOM are induced by fatigue and designed to lower the stress on core muscles.

In our opinion, another important kinematic modification related to the diminished forward lean of the body is the alteration in the displacement of the elbow joint that occurs during the first part of the poling phase on the second section. The elbow angle at pole plant was the same on both sections, but the minimal angle that typically occurs after 10–12% of

**TABLE 1 |** Anthropometric and performance characteristics of the 10 skiers who fulfilled the criteria for inclusion.

| | Mean ± SD of the 10 athletes analyzed |
|---|---|
| Age (years) | 32 ± 6 |
| Height (m) | 1.80 ± 0.05 |
| Weight (kg) | 74 ± 4 |
| FIS points | 139 ± 71 |

*FIS points are referred to the list relative to the period just before the race.*

**TABLE 2 |** Cycle characteristics, range of motion (ROM) of joints, antero-posterior (θCOM) and vertical (*z*COM) displacement of the COM on the first and second sections filmed.

| | First section | Second section | *P*-value |
|---|---|---|---|
| Cycle velocity (km·h$^{-1}$) | 24.3 ± 0.9 | 22.5 ± 0.8 | **0.000** |
| Cycle duration (s) | 1.10 ± 0.09 | 1.04 ± 0.07 | 0.153 |
| Cycle frequency (Hz) | 0.92 ± 0.07 | 0.96 ± 0.06 | 0.155 |
| Cycle length (m) | 7.45 ± 0.51 | 6.58 ± 0.53 | **0.002** |
| Poling time (s) | 0.29 ± 0.02 | 0.30 ± 0.02 | 0.295 |
| Poling time (% of cycle duration) | 26.0 ± 3.1 | 28.9 ± 2.6 | **0.034** |
| Shoulder ROM (°) | 105 ± 14 | 108.1 ± 17.5 | 0.699 |
| Elbow ROM (°) | 112 ± 14 | 98 ± 16 | **0.045** |
| Hip ROM (°) | 91.3 ± 7.0 | 99.1 ± 11.9 | 0.090 |
| Knee ROM (°) | 31.5 ± 5.3 | 35.7 ± 8.6 | 0.205 |
| Ankle ROM (°) | 15.1 ± 4.2 | 17.3 ± 3.8 | 0.225 |
| θCOM ROM (°) | 18.5 ± 3.2 | 19.5 ± 3.6 | 0.517 |
| zCOM ROM (% of body height) | 16 ± 3 | 17 ± 2 | 0.534 |

*The values presented are means ± SD. The P-values for the differences were determined with Student's t-test, with values < 0.05 being considered statistically significant. m, meter; s, second; ROM, range of motion; θCOM, incline of the body respect to the vertical line; zCOM, vertical position of the COM.*

**TABLE 3 |** Minimal (min) and maximal (max) pole and joint angles, as well as displacement of the COM, on the first and second sections filmed, as well as at specific phases of the double poling cycle (PP, pole plant; PO, end of the poling phase).

| | | First section | Second section | *P*-value |
|---|---|---|---|---|
| Pole angle | at PP | 80 ± 2 | 79 ± 2 | 0.378 |
| | at PO | 23 ± 2 | 23 ± 1 | 0.988 |
| Shoulder angle | at PP | 65.7 ± 10.3 | 77.6 ± 13.2 | **0.037** |
| | at PO | 13.2 ± 7.8 | 19.2 ± 10.5 | 0.164 |
| | Min | −27.7 ± 8.9 | −24.3 ± 11.0 | 0.456 |
| | Max | 77.6 ± 8.8 | 83.8 ± 13.1 | 0.230 |
| Elbow angle | at PP | 81.0 ± 10.3 | 87.7 ± 17.2 | 0.307 |
| | at PO | 152.6 ± 8.7 | 152.9 ± 15.2 | 0.959 |
| | Min | 58.0 ± 11.1 | 72.5 ± 13.9 | **0.019** |
| | max | 171.0 ± 9.0 | 170.5 ± 13.4 | 0.929 |
| Hip angle | at PP | 133.3 ± 5.4 | 128.5 ± 14.1 | 0.325 |
| | at PO | 75.9 ± 8.0 | 76.0 ± 7.8 | 0.967 |
| | min | 75.5 ± 8.1 | 74.9 ± 7.8 | 0.874 |
| | max | 166.8 ± 5.7 | 174.0 ± 11.5 | 0.092 |
| Knee angle | at PP | 146.9 ± 5.7 | 147.0 ± 12.1 | 0.984 |
| | at PO | 139.2 ± 6.8 | 141.0 ± 5.8 | 0.529 |
| | min | 136.4 ± 6.4 | 137.4 ± 7.2 | 0.753 |
| | max | 167.9 ± 6.6 | 173.1 ± 9.3 | 0.167 |
| Ankle angle | at PP | 97.8 ± 4.1 | 106.3 ± 9.3 | **0.017** |
| | at PO | 103.8 ± 2.9 | 114.8 ± 9.0 | **0.002** |
| | min | 93.6 ± 2.6 | 101.6 ± 10.5 | **0.032** |
| | max | 108.7 ± 5.8 | 118.9 ± 8.6 | **0.006** |
| θCOM angle | at PP | 11.6 ± 3.2 | 8.2 ± 3.3 | **0.030** |
| | at PO | −4.1 ± 2.1 | −9.2 ± 3.9 | **0.002** |
| | min | −5.4 ± 2.2 | −10.1 ± 4.1 | **0.004** |
| | max | 13.2 ± 2.9 | 9.4 ± 3.0 | **0.012** |
| zCOM (% of body height) | at PP | 56 ± 2 | 55 ± 3 | 0.504 |
| | at PO | 44 ± 2 | 44 ± 3 | 0.859 |
| | Min | 43 ± 2 | 43 ± 3 | 0.998 |
| | Max | 60 ± 3 | 60 ± 4 | 0.693 |

*All angles are given in degrees and the values presented as means ± SD. The P-values for the differences were determined with Student's t-test, with values < 0.05 being considered statistically significant. θCOM, incline of the body respect to the vertical line; zCOM, vertical position of the COM.*

the cycle duration (Lindinger et al., 2009; Zoppirolli et al., 2013) was increased significantly on the second section, thus attenuating the range of flexion that precedes the extension phase. Other investigators have suggested that with an initial double poling velocity of 16 km·h$^{-1}$, a stretch-shortening cycle occurs in the extensor muscles of the arm immediately after pole plant, during the flexion-extension of the elbow joint (Lindinger et al., 2009; Zoppirolli et al., 2013). Thus, the limited angular range of the elbow joint on the second section probably reflects a reduced capacity of these extensors for sustaining eccentric work. Indeed, exhausting exercise involving stretch-shortening cycles has a more detrimental effect on the performance of these cycles themselves than on concentric performance, indicating that tolerance to repeated stretch declines as fatigue increases (Horita et al., 2003). In the case of purely eccentric exercise, impairment of muscle function following prolonged or exhaustive cycles of stretch-shortening has been proposed to arise from structural alterations, acute pro-inflammatory processes, accumulation of biochemical products and/or altered sensitivity of the stretch reflex and reduction in muscle stiffness during the eccentric phase of the exercise (Basmajian and De Luca, 1985; Sahlin, 1985; Green, 1997; Avela and Komi, 1998; Komi, 2000; Laaksonen et al., 2006).

## Cycle Length and the Duty Factor

The observation that cycle length is reduced on the second section while poling time remained unaltered here may reflect less total impulse during the poling action, i.e., a reduction in poling force. In the fatigued state, less effective dynamic contractions are due to slower development of force (Morel et al., 2015). In this context, an earlier report documented a detrimental effect of fatigue, induced by long-distance classical skiing, on the rate of force development by arm muscles (Boccia et al., 2016). Moreover, short-term, high-intensity skiing in the laboratory attenuates the ability to exert poling force significantly (Mikkola et al., 2013; Zoppirolli et al., 2016).

However, the poling force exerted during double poling by high-level cross-country skiers is related not only to muscle strength, but also depends on their technique, i.e., the expert use of body weight to transfer force to the pole. More specifically, the higher the forward lean of the body (i.e., the θCOM) during the early poling phase, the higher the poling force (Zoppirolli et al., 2015, 2016). Although earlier studies showed little change in joint angles or displacement of the COM following maximal-intensity double poling of short duration (Zory et al., 2009; Zoppirolli et al., 2016), we found significant changes in the angles of the shoulder, elbow and ankle joints, as well as in the forward displacement of the COM relative to the feet (θCOM).

The reduction in the cycle length of elite cross-country skiers after 50 km of double poling racing can thus be interpreted as attenuated effectiveness of the poling action. This could be the result of lower capacity for propulsion through the poles due to muscle fatigue, reduced effectiveness of the stretch-shortening cycle of the arm extensor muscles, and/or less effective exploitation of body weight. Another important finding here was that, in agreement with the signs of progressive fatigue observed in connection with prolonged running (Vernillo et al., 2014; Giovanelli et al., 2017), the duty factor (i.e., the percentage of the cycle time accounted for by the poling phase) rose. Although cycle time was significantly lower on the second section, the duration of the poling phase was not reduced to the same extent, remaining similar to that on the first section (**Table 2**).

An elevated duty factor means relatively less time for muscle relaxation (Green, 1997). The higher percentage of the cycle time dedicated to propulsion probably reflects a reduced capacity of the arm extensor muscles to produce force rapidly. Boccia et al. (2016) suggested that the type of race examined here lowers the rate of voluntary force development by the elbow extensors, due to mechanical rather than neural reasons. At the same time, the shorter recovery phase means less blood flow through the muscles, possibly lowering ATP supplementation and the removal of metabolites (Green, 1997), as well as less time for repositioning the body properly for the subsequent propulsive phase.

Although the effects of utilizing double poling exclusively versus choosing a mixture of skiing techniques have never been compared systematically, our present findings reveal that racing for 2 h with only double poling alters whole-body kinematics and reduces effective propulsion.

## METHODOLOGICAL CONSIDERATIONS: SKIING ON-SNOW VERSUS ON A TREADMILL

In these final paragraphs, the reliability of our field-tracking methodology is assessed further by comparing our values for joint angles and displacement of the COM to those obtained by optoelectronic Motion Capture in laboratory studies. In particular the angles at the elbow, hip, knee and ankle joints on the first section here, when double poling velocity averaged 24.3 ± 0.9 $km \cdot h^{-1}$, can be compared to the findings of Holmberg et al. (2005) for double poling on roller skies at 24.5 ± 1.4 $km \cdot h^{-1}$ on a treadmill at a 1° incline. In addition, the displacements in *z*COM and θCOM on the second section, when the mean double poling velocity was 22.5 ± 0.8 $km \cdot h^{-1}$, can be compared to our previous observations concerning double poling kinematics while roller skiing at 20.0 $km \cdot h^{-1}$ on a treadmill at a 1° incline (Zoppirolli et al., 2016).

All of the joints analyzed exhibited the typical flexion-extension pattern observed in the laboratory. More specifically, the elbow joint angle was approximately 80° at PP and 160° at PO, with maximal extension of about 170° after approximately 35% of the cycle time, both here on snow and in the laboratory (see **Table 3** and **Figure 5**, Holmberg et al., 2005). Even though the first phase of elbow joint flexion occupies approximately 10% of the cycle time in both these situations, the range of flexion was somewhat narrower on snow (with a minimum of 60° versus 50°, see **Figure 4**; Holmberg et al., 2005). In both situations as well, the hip joint angle was approximately 15° at PP, with maximal displacement of around 170° after 80% of the cycle time. Although this hip angle was minimal after 25% of the cycle in both cases, the range of flexion-extension was more pronounced on snow (a minimum of 80° versus 105° on a treadmill).

The displacements of the knee and ankle joints on snow were comparable to those in the laboratory only in a few portions of the cycle. Although the timing of flexion-extension is the same in both situations, the maximal angles of extension at both the knee (165°) and ankle (105°) after approximately 80% and 90% of the cycle time, respectively, were the only absolute angles that were similar. Indeed, when skiing on snow these joints are 10°–15° more extended during the rest of the cycle (see **Figure 4**, Holmberg et al., 2005).

Equally detailed comparison of the COM displacement is not possible, since Zoppirolli et al. (2016) assessed this parameter in the laboratory at only a few time-points during the DP cycle. When skiing on snow at approximately 22 $km \cdot h^{-1}$, the θCOM here was about 8° at PP and −3° at PO, as was also the case on a treadmill. Moreover, the position of *z*COM (expressed as a percentage of body height) follows the same pattern in both situations, with comparable minimal and maximal values at PO and after 80% of the cycle, respectively (see **Table 3** and **Figure 5**; Zoppirolli et al., 2016).

In our opinion, these discrepancies between our findings and previous laboratory results concerning the displacement of joints and COM during a cycle of double poling reflect both differences in experimental conditions and the protocols employed. For example, the smaller range of flexion of the elbow joint on snow is probably due to the lower resistance of the snow than the treadmill to pole plant. At equal speed, double poling on snow should require less extensive stretch-shortening of arm extensors and, at the same time, put less stress on the shoulder and elbow joints. In contrast, the differences concerning the hip, knee and ankle joints can be ascribed to the different testing protocols, i.e., double poling on snow for several hours versus short-term double poling on a treadmill.

Overall, we conclude that our careful positioning of the video cameras, calibration of the tracks, choice of inclusion criteria and tracking procedures have provided reliable kinematic information. Indeed, both the displacement of joints and COM and the absolute values, pattern and timing of flexion-extension on the two sections filmed were highly similar to what has been observed in the laboratory. Experimental measurements in the field are challenging, especially with actual on-snow racing, with its changing environment, problems with instrumentation due to the temperature and reflections from the snow, lack of reference points for space calibration, etc. However, we demonstrate here that careful and rigorous methodology allows precise and reliable kinematic analysis, even under these difficult conditions.

## CONCLUSION

Racing for 2 h exclusively with double poling only affects the whole-body kinematics of elite cross-country skiers, even though they maintained their cycle frequency, irrespective of the actual velocity. Less effective positioning of the COM and altered flexion-extension of the elbow joint during the early portion of the poling phase were the major kinematic alterations observed. These changes, together with muscle fatigue, probably reduce the generation of poling force and thus cycle velocity with time. To minimize such detrimental effects, elite skiers should train maintaining optimal elbow and ankle kinematics and an efficient forward lean of the body during the propulsive phase of double poling, even when fatigued. As already mentioned, the technical training requires also specific focus on the strength and endurance of core, abdominal, and arm muscles.

## ETHICS STATEMENT

This study was pre-approved by the Ethical Committee of Verona University (prot. n° 5984/2015), as part of the project "MarcialongaScience" proposed by the University of Verona and the Marcialonga Organizing Committee. When signing up for the race, the athletes gave their permission to be video-filmed. The present investigation contains data obtained from video-recordings.

## AUTHOR CONTRIBUTIONS

CZ, BP, LB, and FSc contributed substantially to the conception and design of this study. CZ, BP, and LB contributed to data collection. CZ and FSt carried out the data analysis and interpretation together with BP, GB, and H-CH. CZ wrote the first draft of the manuscript and all authors were involved in revising it critically. CZ, BP, LB, FSt, GB, FSc, and H-CH gave final approval of the version to be published and agreed to be accountable for all aspects of this work.

## ACKNOWLEDGMENTS

We would like to thank the Marcialonga Organizing Committee for their collaboration and logistic support during testing. Moreover, we offer our sincere thanks to Massimiliano Prosser and Chiara Groff, the students who helped with the tracking.

## REFERENCES

Abbiss, C. R., and Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Med.* 38, 239–252. doi: 10.2165/00007256-200838030-00004

Asan Grasaas, C., Ettema, G., Hegge, A. M., Skovereng, K., and Sandbakk, O. (2014). Changes in technique and efficiency after high-intensity exercise in cross-country skiers. *Int. J. Sports Physiol. Perform.* 9, 19–24. doi: 10.1123/ijspp.2013-0344

Avela, J., and Komi, P. V. (1998). Reduced stretch reflex sensitivity and muscle stiffness after long-lasting stretch-shortening cycle exercise in humans. *Eur. J. Appl. Physiol. Occup. Physiol.* 78, 403–410. doi: 10.1007/s004210050438

Basmajian, J. V., and De Luca, C. J. (1985). *Muscles Alive.* Baltimore, MD: Williams & Wilkins.

Bereket, S. (2005). Effects of anthropometric parameters and stride frequency on estimation of energy cost of walking. *J. Sports Med. Phys. Fitness* 45, 152–161.

Boccia, G., Dardanello, D., Zoppirolli, C., Bortolan, L., Cescon, C., Schneebeli, A., et al. (2016). Central and peripheral fatigue in knee and elbow extensor muscles after a long-distance cross-country ski race. *Scand. J. Med. Sci. Sports* 27, 945–955. doi: 10.1111/sms.12718

Brisswalter, J., Hausswirth, C., Smith, D., Vercruyssen, F., and Vallier, J. M. (2000). Energetically optimal cadence vs. freely-chosen cadence during cycling: effect of exercise duration. *Int. J. Sports Med.* 21, 60–64. doi: 10.1055/s-2000-8857

Budde, R., and Himes, A. (2017). High-resolution friction measurements of cross-country ski bases on snow. *Sports Eng.* 20, 299–311. doi: 10.1007/s12283-017-0230-5

Carlsson, M., Assarsson, H., and Carlsson, T. (2016). The influence of sex, age, and race experience on pacing profiles during the 90 km Vasaloppet ski race. *Open Access J. Sports Med.* 7, 11–19. doi: 10.2147/OAJSM.S101995

de Ruiter, C. J., Verdijk, P. W., Werker, W., Zuidema, M. J., and de Haan, A. (2014). Stride frequency in relation to oxygen consumption in experienced and novice runners. *Eur. J. Sport Sci.* 14, 251–258. doi: 10.1080/17461391.2013.783627

Giovanelli, N., Taboga, P., and Lazzer, S. (2017). Changes in running mechanics during a 6-hour running race. *Int. J. Sports Physiol. Perform.* 12, 642–647. doi: 10.1123/ijspp.2016-0135

Green, H. J. (1997). Mechanisms of muscle fatigue in intense exercise. *J. Sports Sci.* 15, 247–256. doi: 10.1080/026404197367254

Hanley, B. (2016). Pacing, packing and sex-based differences in Olympic and IAAF world championship marathons. *J. Sports Sci.* 34, 1675–1681. doi: 10.1080/02640414.2015.1132841

Hansen, E. A., and Smith, G. (2009). Factors affecting cadence choice during submaximal cycling and cadence influence on performance. *Int. J. Sports Physiol. Perform.* 4, 3–17. doi: 10.1123/ijspp.4.1.3

Holmberg, H. C., Lindinger, S. J., Stöggl, T., Eitzlmair, E., and Müller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sports Exerc.* 37, 807–818. doi: 10.1249/01.MSS.0000162615.47763.C8

Horita, T., Komi, P. V., Hamalainen, I., and Avela, J. (2003). Exhausting stretch-shortening cycle (SSC) exercise causes greater impairment in SSC performance than in pure concentric performance. *Eur. J. Appl. Physiol.* 88, 527–534. doi: 10.1007/s00421-002-0716-z

Hunter, I., and Smith, G. A. (2007). Preferred and optimal stride frequency, stiffness and economy: changes with fatigue during a 1-h high-intensity run. *Eur. J. Appl. Physiol.* 100, 653–661. doi: 10.1007/s00421-007-0456-1

Jones, G. M., and Watt, D. G. D. (1971). Observations on the control of stepping and hopping movements in man. *J. Physiol.* 219, 709–727. doi: 10.1113/jphysiol.1971.sp009684

Komi, P. V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J. Biomech.* 33, 1197–1206. doi: 10.1016/S0021-9290(00)00064-6

Laaksonen, M. S., Kivela, R., Kyrolainen, H., Sipila, S., Selanne, H., Lautamaki, R., et al. (2006). Effects of exhaustive stretch-shortening cycle exercise on muscle blood flow during exercise. *Acta Physiol.* 186, 261–270. doi: 10.1111/j.1748-1716.2006.01532.x

Leirdal, S., Sandbakk, O., and Ettema, G. (2013). Effects of frequency on gross efficiency and performance in roller ski skating. *Scand. J. Med. Sci. Sports* 23, 295–302. doi: 10.1111/j.1600-0838.2011.01379.x

Lindinger, S. J., and Holmberg, H. C. (2011). How do elite cross-country skiers adapt to different double poling frequencies at low to high speeds? *Eur. J. Appl. Physiol.* 111, 1103–1119. doi: 10.1007/s00421-010-1736-8

Lindinger, S. J., Holmberg, H. C., Muller, E., and Rapp, W. (2009). Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. *Eur. J. Appl. Physiol.* 106, 353–363. doi: 10.1007/s00421-009-1018-5

Losnegard, T., Kjeldsen, K., and Skattebo, O. (2016). An analysis of the pacing strategies adopted by elite cross-country skiers. *J. Strength Cond. Res.* 30, 3256–3260. doi: 10.1519/JSC.0000000000001424

Masters, K. S., and Ogles, B. M. (1998). The relations of cognitive strategies with injury, motivation, and performance among marathon runners: results from two studies. *J. Appl. Sports Psychol.* 10, 281–296. doi: 10.1080/10413209808406394

Mikkola, J., Laaksonen, M. S., Holmberg, H. C., Nummela, A., and Linnamo, V. (2013). Changes in performance and poling kinetics during cross-country sprint skiing competition using the double-poling technique. *Sports Biomech.* 12, 355–364. doi: 10.1080/14763141.2013.784798

Millet, G. Y., and Lepers, R. (2004). Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med.* 34, 105–116. doi: 10.2165/00007256-200434020-00004

Morel, B., Rouffet, D. M., Saboul, D., Rota, S., Clemencon, M., and Hautier, C. A. (2015). Peak torque and rate of torque development influence on repeated maximal exercise performance: contractile and neural contributions. *PLoS One* 10:e0119719. doi: 10.1371/journal.pone.0119719

Morgan, W. P., and Pollock, M. L. (1977). Psychologic characterization of the elite distance runner. *Ann. N. Y. Acad. Sci.* 301, 382–403. doi: 10.1111/j.1749-6632.1977.tb38215.x

Nicol, C., Avela, J., and Komi, P. V. (2006). The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Med.* 36, 977–999. doi: 10.2165/00007256-200636110-00004

Sahlin, K. (1985). Muscle fatigue and lactic acid accumulation. *Acta Physiol. Scand.* 556, 83–91.

Sandbakk, O., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sandbakk, Ø., Holmberg, H. C., Leirdal, S., and Ettema, G. (2011). The physiology of world class sprint skiers. *Scand. J. Med. Sci. Sports* 21, e9–e16. doi: 10.1111/j.1600-0838.2010.01117.x

Schena, F., Pellegrini, B., Tarperi, C., Calabria, E., Salvagno, G. L., and Capelli, C. (2014). Running economy during a simulated 60-km trial. *Int. J. Sports Physiol. Perform.* 9, 604–609. doi: 10.1123/ijspp.2013-0302

Stöggl, T., Mueller, E., Ainegren, M., and Holmberg, H. C. (2010). General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand. J. Med. Sci. Sports* 21, 791–803. doi: 10.1111/j.1600-0838.2009.01078.x

Stöggl, T., and Müller, E. (2009). Kinematic determinants and physiological response of cross-country skiing at maximal speed. *Med. Sci. Sports Exerc.* 41, 1476–1487. doi: 10.1249/MSS.0b013e31819b0516

Tenenbaum, G. A. (2001). A social-cognitive perspective of perceived exertion and exertion tolerance. *Handb. Sports Psychol.* 2, 810–820.

Vernillo, G., Savoldelli, A., Zignoli, A., Trabucchi, P., Pellegrini, B., Millet, G. P., et al. (2014). Influence of the world's most challenging mountain ultra-marathon on energy cost and running mechanics. *Eur. J. Appl. Physiol.* 114, 929–939. doi: 10.1007/s00421-014-2824-y

Welde, B., Stoggl, T. L., Mathisen, G. E., Supej, M., Zoppirolli, C., Winther, A. K., et al. (2017). The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *PLoS One* 12:e0187111. doi: 10.1371/journal.pone.0187111

Zoppirolli, C., Boccia, G., Bortolan, L., Schena, F., and Pellegrini, B. (2017). Functional significance of extent and timing of muscle activation during double poling on-snow with increasing speed. *Eur. J. Appl. Physiol*. 117, 2149–2157. doi: 10.1007/s00421-017-3703-0

Zoppirolli, C., Holmberg, H. C., Pellegrini, B., Quaglia, D., Bortolan, L., and Schena, F. (2013). The effectiveness of stretch-shortening cycling in upper-limb extensor muscles during elite cross-country skiing with the double-poling technique. *J. Electromyogr. Kinesiol.* 23, 1512–1519. doi: 10.1016/j.jelekin.2013.08.013

Zoppirolli, C., Pellegrini, B., Bortolan, L., and Schena, F. (2015). Energetics and biomechanics of double poling in regional and high-level cross-country skiers. *Eur. J. Appl. Physiol.* 115, 969–979. doi: 10.1007/s00421-014-3078-4

Zoppirolli, C., Pellegrini, B., Bortolan, L., and Schena, F. (2016). Effects of short-term fatigue on biomechanical and physiological aspects of double poling in high-level cross-country skiers. *Hum. Mov. Sci.* 47, 88–97. doi: 10.1016/j.humov.2016.02.003

Zory, R., Millet, G., Schena, F., Bortolan, L., and Rouard, A. (2006). Fatigue induced by a cross-country skiing KO sprint. *Med. Sci. Sports Exerc.* 38, 2144–2150. doi: 10.1249/01.mss.0000235354.86189.7e

Zory, R., Molinari, F., Knaflitz, M., Schena, F., and Rouard, A. (2011). Muscle fatigue during cross country sprint assessed by activation patterns and electromyographic signals time-frequency analysis. *Scand. J. Med. Sci. Sports* 21, 783–790. doi: 10.1111/j.1600-0838.2010.01124.x

Zory, R., Vuillerme, N., Pellegrini, B., Schena, F., and Rouard, A. (2009). Effect of fatigue on double pole kinematics in sprint cross-country skiing. *Hum. Mov. Sci.* 28, 85–98. doi: 10.1016/j.humov.2008.05.002

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer RF and handling Editor declared their shared affiliation at time of review.

ORIGINAL RESEARCH
published: 19 July 2018
doi: 10.3389/fphys.2018.00932

# Effects of Different Training Intensity Distributions Between Elite Cross-Country Skiers and Nordic-Combined Athletes During Live High-Train Low

**Laurent Schmitt[1,2], Sarah J. Willis[2], Nicolas Coulmy[3] and Gregoire P. Millet[2]***

*[1] National School of Mountain Sports/National Ski-Nordic Centre, Premanon, France, [2] Institute of Sport Sciences, Faculty of Biology and Medicine, University of Lausanne, Lausanne, Switzerland, [3] French Ski Federation, Annecy, France*

OPEN ACCESS

**Edited by:**
Martin Burtscher,
Universität Innsbruck, Austria

**Reviewed by:**
Ginés Viscor,
University of Barcelona, Spain
Thomas Leonhard Stöggl,
University of Salzburg, Austria

***Correspondence:**
Gregoire P. Millet
gregoire.millet@unil.ch

**Specialty section:**
This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology

**Received:** 24 March 2018
**Accepted:** 25 June 2018
**Published:** 19 July 2018

**Citation:**
Schmitt L, Willis SJ, Coulmy N and Millet GP (2018) Effects of Different Training Intensity Distributions Between Elite Cross-Country Skiers and Nordic-Combined Athletes During Live High-Train Low. Front. Physiol. 9:932. doi: 10.3389/fphys.2018.00932

**Purpose:** To analyze the effects of different training strategies (i.e., mainly intensity distribution) during living high – training low (LHTL) between elite cross-country skiers and Nordic-combined athletes.

**Methods:** 12 cross-country skiers (XC) (7 men, 5 women), and 8 male Nordic combined (NC) of the French national teams were monitored during 15 days of LHTL. The distribution of training at low-intensity (LIT), below the first ventilatory threshold (VT1), was 80% and 55% in XC and NC respectively. Daily, they filled a questionnaire of fatigue, and performed a heart rate variability (HRV) test. Prior (Pre) and immediately after (Post), athletes performed a treadmill incremental running test for determination of $\dot{V}O_{2max}$ and $\dot{V}O_2$ at the second ventilatory threshold ($\dot{V}O_{2VT2}$), a field roller-skiing test with blood lactate ([La-]) assessment.

**Results:** The training volume was in XC and NC, respectively: at LIT: 45.9 ± 6.4 vs. 23.9 ± 2.8 h ($p < 0.001$), at moderate intensity: 1.9 ± 0.5 vs. 3.0 ± 0.4 h, ($p < 0.001$), at high intensity: 1.2 ± 0.9 vs. 1.4 ± 02 h ($p = 0.05$), in strength (and jump in NC): 7.1 ± 1.5 vs. 18.4 ± 2.7 h, ($p < 0.001$). Field roller-skiing performance was improved (−2.9 ± 1.6%, $p < 0.001$) in XC but decreased (4.1 ± 2.6%, $p < 0.01$) in NC. [La-] was unchanged (−4.1 ± 14.2%, $p = 0.3$) in XC but decreased (−27.0 ± 11.1%, $p < 0.001$) in NC. Changes in field roller-skiing performance and in [La-] were correlated ($r = -0.77$, $p < 0.001$). $\dot{V}O_{2max}$ increased in both XC and NC (3.7 ± 4.2%, $p = 0.01$ vs. 3.7 ± 2.2%, $p = 0.002$) but $\dot{V}O_{2VT2}$ increased only in XC (7.3 ± 5.8%, $p = 0.002$). HRV analysis showed differences between XC and NC mainly in high spectral frequency in the supine position ($HF_{SU}$). All NC skiers showed some signs of overreaching at Post.

**Conclusion:** During LHTL, despite a higher training volume, XC improved specific performance and aerobic capacities, while NC did not. All NC skiers showed fatigue states. These findings suggest that a large amount of LIT with a moderate volume of strength and speed training is required during LHTL in endurance athletes.

**Keywords: altitude training, performance, Nordic-ski, fatigue, heart rate variability**

# INTRODUCTION

Live high train low (LHTL) is a hypoxic training method used by many endurance athletes (Stray-Gundersen and Levine, 1999). If correctly prescribed and monitored, LHTL has been shown to be effective for endurance athletes, including those with an initial high aerobic fitness or hemoglobin mass (Millet et al., 2017). Based on 20 years of research since the original study in Levine and Stray-Gundersen (1997), LHTL is known for inducing a 1–3% larger improvement in specific endurance performance, when compared to similar normoxic training (Bonetti and Hopkins, 2009; Millet et al., 2010). However, the responses to altitude training remain complex since hypoxia and training stresses are combined (Schmitt et al., 2006). In hypoxia, the reduced inspired pressure of oxygen ($PiO_2$) represents an additional stress, which has been shown to alter the autonomous regulation of the nervous system and subsequently to modify responses in heart rate variability (HRV) (Schmitt et al., 2006) with a combination of increased sympathetic and decreased parasympathetic nervous activities (Sevre et al., 2001; Schmitt et al., 2006). Schmitt et al. (2006, 2008) have shown that HRV parameters are modified differently depending on the intensity of training performed in altitude. Specifically, the combination of moderate altitude (<3000 m) and low intensity training (LIT), below the first ventilatory threshold (VT1), has been shown to be quite favorable to the development of aerobic capacities (Schmitt et al., 2006, 2008). Conversely, high-intensity exercises and the training loads (TL) have to be reduced, particularly during the first 7–10 days of an altitude training camp (Millet et al., 2010). In the case that the recovery capacities of an athlete are compromised, the athlete enters an overreached state. In this case, HRV parameters help diagnosing different fatigue states (Schmitt et al., 2013, 2015).

It is of practical interest to compare different groups of athletes performing LHTL. *Cross-country (XC) skiers* and *Nordic-combined (NC) athletes* have different characteristics and training contents as reported in Norwegian elite athletes (Sandbakk et al., 2016): In XC skiers, the total annual volume was on average 794 h with 646 h (81%) of LIT, 31 h (4%) of moderate-intensity training (MIT), 46 h (6%) of high-intensity training (HIT), and 71 h (9%) of strength and speed training. In NC athletes, the total annual volume was 836 h with 435 h (52%) of LIT (representing 87% of the XC ski training), 24 h (3%) of MIT, 39 h (5%) of HIT and 338 h (40%) of strength, speed, and jump training (Sandbakk et al., 2016). It appears than the XC ski training is "polarized" (LIT > 75% of total training, 81 vs. 87%) in both XC skiers and NC athletes, whereas the total volume of aerobic training was logically much higher in XC skiers (646 vs. 435 h).

It remains unknown if these differences in training content could influence the responses to LHTL in *XC skiers* and *NC athletes*. Therefore, in the present study, we aimed to analyze the effects on performance, maximal oxygen uptake, and HRV of LHTL (same altitude, same location) in two groups of XC skiers and NC athletes. We tested the hypothesis that during the LHTL period, a difference in low-intensity training volume (with the biggest amount of LIT in XC) and more strength and speed volume would induce less HRV perturbation, fewer fatigue states, and larger aerobic and performance improvement.

# MATERIALS AND METHODS

## Subjects

Subjects were 20 elite Nordic-skiers, members of the *XC skiing* and *NC* French national teams. The characteristics of subjects were:

XC skiers group: 7 men (22.6 ± 2.8 year, 73.6 ± 5.9 kg, 179.9 ± 5.4 cm, $\dot{V}O_{2max}$ 69.3 ± 3.6 $mL \cdot kg^{-1} \cdot min^{-1}$), and 5 women (22.8 ± 4.1 year, 55.6 ± 4.4 kg, 163.6 ± 5.2 cm, $\dot{V}O_{2max}$ 58.9 ± 2.5 $mL \cdot kg^{-1} \cdot min^{-1}$).

NC group: 8 men (23.5 ± 4.5 year, 65.8 ± 3.1 kg, 176.3 ± 4.3 cm, $\dot{V}O_{2max}$ 66.1 ± 3.2 $mL.ckg^{-1} \cdot min^{-1}$).

All these athletes competed in European cup or World cup levels and some were medalists in World championships.

## Experimental Design

The study design is shown in **Figure 1**. The study was approved by the local ethical committees (French National Conference of Research Ethics Committees; N°CPP EST I: 2014/33; Dijon, France). All experimental procedures conformed to the standards set by the Declaration of Helsinki (Harriss and Atkinson, 2015). All subjects provided written informed consent to participate in the study after having been informed in detail about the experimental procedure. Exclusion criteria for participation were any history of altitude-related sickness and health risks that could compromise the subject's safety during training and/or hypoxic exposure. The study was performed at the French National Ski-Nordic Center which contains 11 hypoxic rooms and is located at an altitude of 1150 m. These hypoxic chambers were of medium size (15 ± 1 $m^2$) and equipped with conventional beds. Two subjects were in each room and primarily spent time sleeping or resting between training sessions. The rooms were in normobaric hypoxic condition with $FiO_2$ = 15.0% (2700 m) of simulated altitude and the training session were at 1150 m of real altitude. No athletes were under any medical treatment during the study.

## Training Performed

The intensity distribution was quantified depending of the time spent in heart rate (HR) zones delimitated by the correspondence between HR and the ventilatory thresholds. The TL was organized in four training zones as presented recently (Solli et al., 2017): *Intensity I* for endurance training at an intensity below VT1; *intensity II* for endurance training at an intensity between VT1 and VT2; *intensity III* for training at an intensity at VT2, interval-training at intensity above VT2, and competitions; and *intensity IV* for strength, speed training sessions, as well as jumping for the NC group.

VT1 corresponds to the first non-linear increases in $\dot{V}CO_2$, and VT2 was determined as the first rise in the ventilatory equivalent of oxygen ($\dot{V}E/\dot{V}O_2$) without a concurrent rise in the ventilatory equivalent of carbon dioxide ($\dot{V}E/\dot{V}CO_2$) (Reinhard et al., 1979).

Training loads were quantified as described previously (Mujika et al., 1996) but slightly adapted to Nordic skiing. TL, expressed in arbitrary units (a.u.), was calculated by multiplying the training duration (in min) spent in each intensity zone by

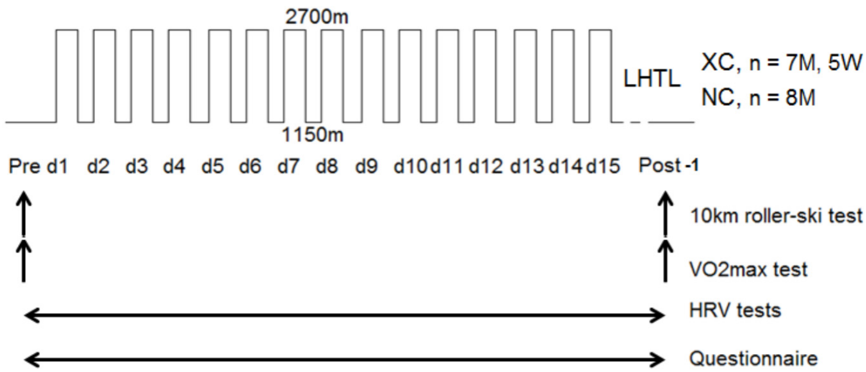


**FIGURE 1 |** Experimental design. Cross-country skiers group (XC, men, *n* = 7, and women, *n* = 5), Nordic-combined group (NC, *n* = 8). The tests performed were a maximal *field* roller-skis test with blood lactate measurements 2 min after the end of exercise, a maximal oxygen uptake ($\dot{V}O_{2max}$) on treadmill, a morning questionnaire upon awakening of fatigue, and an active Tilt test to measure the resting heart rate variability (HRV), and heart rate (HR). Vertical arrows indicate the day of the tests and horizontal arrows define the day-tests period.

a coefficient (i.e., 1, 2, 4, and 8 for the zones I, II, III, and IV, respectively).

For the LHTL intervention, the intensity distributions planned by the national coaches and the main investigator were 80 - 5 - 5 - 10 for the training loads in intensity zones I, II, III, and IV for *XC* and 55 - 15 - 5 - 25 (including 15% jumping) for *NC*.

## Measurements

Measurements were performed 1 day before (Pre) and 1 day after (*Post*) LHTL intervention.

## Performance

A maximal roller-ski test was performed on an official FIS-accredited roller-ski asphalt track of the National French Ski-Nordic Center, with an equal alternation of up and down-hills, and flat parts. The women performed two laps, and the men three laps of 3.3 km in skating technique. Measurements were performed on each subjects' own roller-skis and poles maintaining the same equipment use for each test.

## Lactate

The blood lactate concentration measurements ([La-], mmol.$L^{-1}$) were performed 2 min after the end of the maximal roller-ski test with a Lactate Pro2® analyzer (ARKRAY, Japan).

## Incremental Maximal Treadmill Test

The incremental running treadmill $\dot{V}O_{2max}$ protocol used in the present study is routinely used for the medical follow-up of the French Nordic-skiers in the same laboratory. The test started at 8 km.$h^{-1}$ and 2%-grade for 3 min, followed by 9 km.$h^{-1}$ and 2%-grade for 3 min, 9 km.$h^{-1}$ and 4%-grade for 3 min, 9 km.$h^{-1}$ and 6%-grade, then 10 km.$h^{-1}$ and 6%-grade. Every 3 min, the stage increased first by speed, then by grade until the second ventilatory threshold (VT2) was passed. VT2 assessment was made by visual inspection of graphs of time plotted against each relevant respiratory variable measured during testing. VT2 was determined as the first rise in the ventilatory equivalent of oxygen ($\dot{V}E/\dot{V}O_2$) without a concurrent rise in the ventilatory equivalent of carbon dioxide ($\dot{V}E/\dot{V}CO_2$) (Reinhard et al., 1979). After VT2, the protocol changed to 1 min stages at the same speed while increasing grade to a maximum of 16% until exhaustion. The same protocol was applied at Pre and Post tests. After VT2, the protocol changed to 1 min stages at the same speed while increasing grade to a maximum of 16% until exhaustion. The $\dot{V}O_{2max}$ was determined by the highest 30 s average value. During all tests, HR was continuously monitored using a telemetry based HR monitor (Ambit3 Peak, Suunto®, Vantaa, Finland) and the maximum was obtained for further analysis. Oxygen ($O_2$) and carbon dioxide ($CO_2$) levels were continuously measured and monitored as breath-by-breath values in expired gas (Ultima Cardio 2® gas exchange analysis system, MGC Diagnostics with Breezesuite software, Saint Paul, MN, United States). The flow meter and the gas analyser were calibrated prior to each test with a 3L volume calibration syringe (Hans Rudholph®, Medgraphics), and with a 5% $CO_2$ and 12% $O_2$ gas mixtures (Medgraphics).

## Questionnaire

The questionnaire of the French society of sport medicine (QSFMS) was completed each morning by all athletes. This questionnaire is used routinely by French national teams in various sports (rugby, swimming, Nordic-ski, triathlon...). The state of fatigue was registered when the score exceeded 20 negative items out of 54 (Benhaddad et al., 1999).

## Heart Rate Variability

The protocol of HRV tests is presented in detail in previous articles (Schmitt et al., 2013, 2015). Briefly, the HRV test consisted of a 15-min RR interval recording at rest with 8 min supine (SU) followed by 7 min standing (ST). The HRV recording was performed daily in the morning immediately after waking and voiding the urinary bladder. HRV analyses were performed on RR intervals between the 3rd and 8th min supine, and between the 9th and 14th min standing. Measurement of the interval duration between two R waves of the cardiac electrical activity were performed with a HR monitor (Ambit 3 Peak, Suunto®, Vantaa, Finland). Then the spectral power was calculated with the Fast Fourier Transform (FFT) using a software (Nevrokard® HRV, Medistar, Ljubljana, Slovenia). The power of spectral density was measured by frequency bands in $ms^2.Hz^{-1}$ and the spectral power was expressed in $ms^2$ (Task, 1996). The high frequency (HF) power band (0.15–0.40 Hz) reflects alteration of the parasympathetic influence on the heart and is related to the respiratory sinus arrhythmia (Pomeranz et al., 1985). While the low frequency (LF) power band (0.04–0.15 Hz) is also driven by parasympathetic tone, and presently considered responsible for carrying vagal resonances to either changes in vasomotor tone (often sympathetic) or in central modulation of sympathetic tone (Reyes del Paso et al., 2013). The spectral power in the LF power band has also been shown to be related to fluctuations of arterial blood pressure (Akselrod et al., 1981; Pomeranz et al., 1985) and to baroreflex activity (Goldstein et al., 2011). Both in supine (SU) and in standing (ST) positions, LF and HF were calculated in absolute spectral power units ($ms^2$) and in normalized units (nu) with $LF(nu) = LF/(LF + HF) \times 100$ and $HF(nu) = HF/(HF + LF) \times 100$. The total spectral power (TP) was calculated by adding LF and HF. Additionally, the temporal analysis of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (RMSSD) was assessed.

## Statistical Analysis

In the two groups, XC and NC, data were tested for equality of variance (Fisher–Snedecor *F*-test) and for normality (Shapiro–Wilk test). When both conditions were met, a two-way repeated measures ANOVA [group (XC vs. NC) vs. measurement (Pre and Post)] was performed with pairwise multiple comparison procedures (*post hoc*, Tukey method). When either equality of variance or normality were not satisfied, variables were analyzed for each condition using a Friedman test for repeated measures to determine time effects using pairwise multiple comparison procedures (Bonferroni test). In this case, differences between the groups were tested using a Mann–Whitney rank sum test. The Pearson product moment correlation was applied to analyze the relationship between specific performance and lactate concentration changes. Null hypotheses were rejected at $P < 0.05$. Data are reported as mean and standard deviation (SD). These analyses were completed using SigmaStat 3.5 software (Systat Software, San Jose, CA, United States).

The statistical method used to distinguish the different HRV fatigue patterns in the NC group has been detailed previously (Schmitt et al., 2015, 2016). First, the analysis focuses on the difference in absolute values between no-fatigue and fatigue conditions, where a non-parametric Mann–Witney test was used to analyze the differences. Then, the relative difference between the mean of all no-fatigue and each fatigue state were calculated. The set of relative differences was submitted to a hierarchical clustering on principal components, which includes two steps. Firstly, a principal component analysis (PCA) was performed to disclose the organization of variables and to select the PCA dimensions which embed the main part of variance. Secondly, a hierarchical ascendant classification was performed according to the first dimensions of the PCA. This process limits the statistical signal to noise ratio and delineates clusters of individuals with similar characteristics. These analyses were conducted using the R-statistics software (V3.1.2) with the FactoMineR package.

# RESULTS

## Training Load and Training Content

In the 3 weeks preceding the LHTL intervention, both weekly TL and training volume were not different between XC (1557 ± 141 a.u., 16.0 ± 1.6 h) and NC (1733 ± 304 a.u., 16.5 ± 2.6 h). The training load and training volume of the LHTL period are shown in **Figure 2**. The intensity distribution for both groups are reported in **Table 1**.

## Performance and Lactates

Absolute values at Pre and Post are presented in **Table 2**.

The roller-ski performance was improved (−2.9 ± 1.6%, $p < 0.001$) in XC but decreased (4.1 ± 2.6%, $p < 0.01$) in NC (**Figure 3**). There was a significant group × measurement interaction ($p < 0.001$) (**Table 2**).

[La-] did not change (−4.1 ± 14.2%, $p = 0.3$) in XC but was decreased in NC (−27.0 ± 11.1%, $p < 0.001$). There was a significant group × measurement interaction ($p < 0.001$). A negative correlation ($r = -0.77$, $p < 0.001$) was found between the changes in [La-] and in roller-ski performance time (**Figure 4**).

## Incremental Maximal Treadmill Test

Absolute values at Pre and Post are presented in **Table 2**. From Pre to Post, maximal oxygen uptake ($\dot{V}O_{2max}$) increased in both groups (XC: 65.0 ± 6.2 vs. 67.3 ± 7.1 $mL.mn^{-1}.kg^{-1}$, $p = 0.01$; NC: 65.7 ± 3.1 vs. 68.1 ± 3.2 $mL.mn^{-1}.kg^{-1}$, $p = 0.002$). The percent increase was not different between the two groups (3.7 ± 4.2%, $p = 0.01$ vs. 3.7 ± 2.2%, $p = 0.002$, for XC and NC, respectively). Oxygen consumption at VT2 ($\dot{V}O_{2VT2}$) increased only in XC from Pre to Post-1 (7.3 ± 5.8%, $p = 0.004$ vs. 1.6 ± 4.3%, $p = 0.31$, for XC and NC, respectively).

## Questionnaire QSFMS

None of the XC or NC subjects declared a state of fatigue during the LHTL intervention and no difference in QSFMS scores were found between the groups (1.6 ± 1.5 a.u. in XC vs. 1.2 ± 1.4 a.u. in NC).

## Heart Rate Variability Parameters

The HRV parameters are displayed in **Table 3**. A trend was observed in difference of change between XC and NC (group × measurement interaction) in $HF_{SU}$ ($p = 0.05$) and $RMSSD_{SU}$ ($p = 0.1$).

No fatigue states were observed in XC. In NC, four types of fatigue (F) were statistically sorted: $F(LF_{SU}{}^{+})$ for 1 subject, $F(HF_{SU}{}^{-}\ LF_{ST}{}^{-})$ for 5 subjects, $F(LF^{-}HF^{-})_{ST}$, and $F(LF^{-}HF^{-})_{SU}$ for one subject each (**Figure 5**).

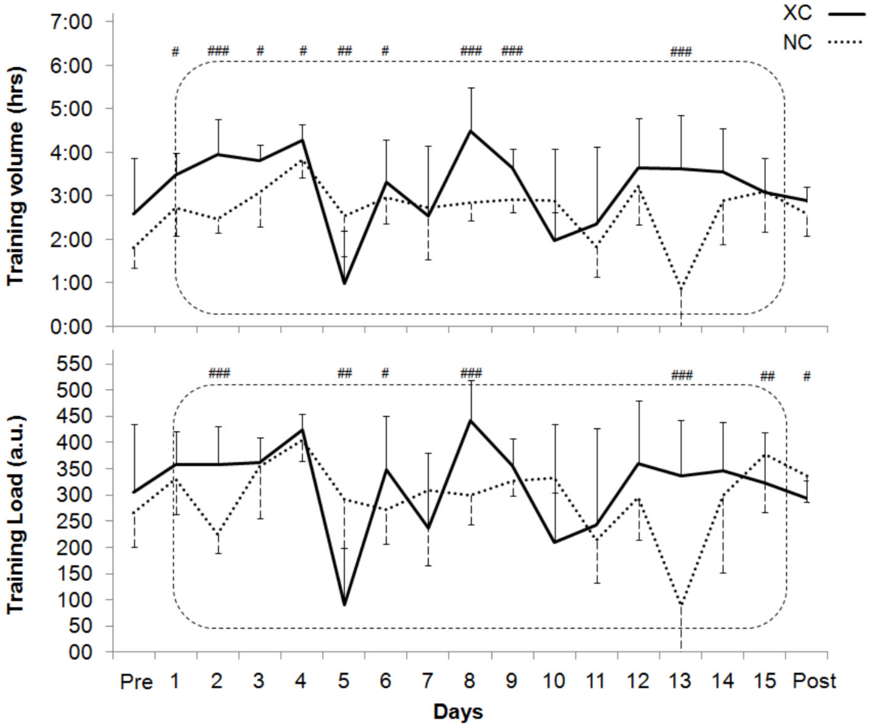


**FIGURE 2 |** Volume of training (h), and training load (TL, in arbitrary unit, a.u.) performed during the Live High - Train Low study in the cross-country skiers (XC) and the Nordic-combined (NC) groups. With # $p < 0.05$, ## $p < 0.01$, ### $p < 0.001$ for differences between XC and NC.

**TABLE 1 |** Content of the training performed in intensity zones with I for low-intensity training (LIT) below the first ventilatory threshold (VT1), II for moderate-intensity training (MIT) between VT1 and second ventilatory threshold (VT2), III for high-intensity training (HIT) upper than VT2, and IV for strength, speed training sessions, and jumping (only for Nordic-combined).

| Groups | Intensity | Volume (h) | *P* | Total training volume (%) | *Cross-country training volume (%)* | *P* |
|---|---|---|---|---|---|---|
| XC | IV | 7.1 ± 1.5 | | 12.9 | | |
| | III | 1.2 ± 0.9 | | 2.2 | 2 | |
| | II | 1.9 ± 0.5 | | 3.4 | 4 | |
| | I | 45.9 ± 6.4 | | 81.6 | 94 | |
| | Total | 56.1 ± 6.5 | | | | |
| NC | IV | 18.4 ± 2.7 | <0.001 | 39.4 | | <0.001 |
| | III | 1.4 ± 0.2 | 0.2 | 3.0 | 5 | 0.05 |
| | II | 3.0 ± 0.4 | <0.001 | 6.5 | 11 | <0.001 |
| | I | 23.9 ± 2.8 | <0.001 | 51.2 | 84 | <0.001 |
| | Total | 46.9 ± 2.9 | <0.001 | | | |

*XC (n = 12) for cross-country skiers, and NC (n = 8) for Nordic-combined. Data are expressed as mean ± SD. P for differences between XC and NC.*

## DISCUSSION

The main findings of this study were:

(1) LHTL induced specific endurance performance enhancement in XC but not in NC skiers, with a larger training volume in XC. The different total training intensity distribution between the two groups: in XC, 82-2-3-13 (i.e., ∼82% of TL < VT1) vs. in NC, 51-6-3-39 (i.e., ∼51% of TL < VT1), led to a specific (roller-skiing) performance enhancement in 100% of the XC subjects whereas it induced a performance decrease in all NC subjects.
(2) This was concomitant to different HRV responses between the groups since only NC athletes displayed fatigue states.

### Training Content and Intensity Distribution

The training content of the present athletes is similar to the values reported in Norwegian athletes (Sandbakk et al., 2016). Of interest is that both TL and training volume were higher in *XC*

**TABLE 2 |** In cross-country (XC) skiers (*n* = 12) and Nordic-combined (NC) athletes (*n* = 8) groups respectively, field maximal roller-skiing test (min.s), Lactates (Mmoles.L$^{-1}$) measured 2 min after the end of the roller-skiing test, maximal oxygen uptake ($\dot{V}O_{2max}$, mL.mn$^{-1}$.kg$^{-1}$), and oxygen consumption at the second ventilatory threshold (VT2) ($\dot{V}O_{2VT2}$, mL.mn$^{-1}$.kg$^{-1}$) at Pre and Post.

| | XC | | NC | | p |
|---|---|---|---|---|---|
| | Pre | Post | Pre | Post | (Groups × Times) |
| Field roller-skiing test (min.s) | 17.2 ± 2.0 | 17.1 ± 1.3 *** | 20.7 ± 0.4 | 21.0 ± 1.0 *** | <0.001 |
| Lactates (Mmoles.L$^{-1}$) | 12.1 ± 2.9 | 11.5 ± 2.8 | 18.2 ± 2.8 | 13.4 ± 3.2 *** | <0.001 |
| Treadmill test $VO_{2max}$ (mL.min$^{-1}$.Kg$^{-1}$) | 65.0 ± 6.2 | 67.3 ± 7.1 ** | 65.7 ± 3.1 | 68.1 ± 3.2 * | 0.98 |
| Treadmill test $VO_{2VT2}$ (mL.min$^{-1}$.Kg$^{-1}$) | 54.7 ± 4.9 | 58.7 ± 5.9 ** | 56.8 ± 4.2 | 58.0 ± 4.6 | 0.05 |

*Data are expressed as mean ± SD in absolute values. With *p < 0.05, **p < 0.01, ***p < 0.001 for Pre vs. Post, and p for two way ANOVA (groups × times interaction).*

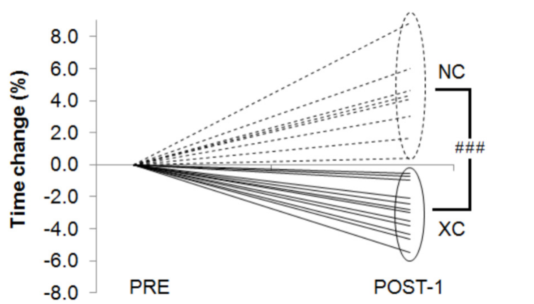


**FIGURE 3 |** Time change (%) in the *field roller-skiing* test between Pre and *Post* in the cross-country skiers (XC) and the Nordic-combined (NC) groups. With ###$p < 0.001$ for differences between XC and NC.

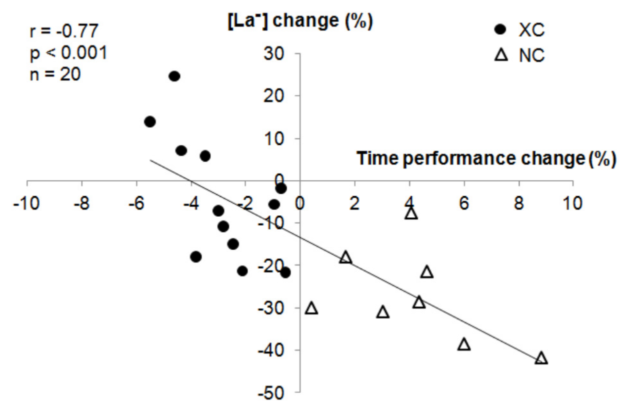


**FIGURE 4 |** Correlation between changes (%) in blood lactate concentration ([La-]) and *maximal field roller-skiing* performance.

*skiers* than in *NC athletes* (**Figure 2** and **Table 1**). The *XC skiing* training performed by both groups is in accordance with the recommendation of the "polarized training" '75-5-20' by Seiler (2010).

The training method named "polarized training" emphasizes the major influence of a high training volume performed at LIT (e.g., below the first ventilatory threshold, VT1) (Seiler and Kjerland, 2006). At the other range of the intensities spectrum, HIT is also a critical training component of all successful endurance athletes. It has been suggested (Seiler and Kjerland, 2006) that a '75-5-20' training load (TL) distribution across the three intensity zones demarcated by VT1 and the second ventilatory threshold (VT2) would be optimal. Recently the intensity distribution '92-3-5' was reported in the World's most successful female *XC* skier over a 12-year period (Solli et al., 2017). Furthermore, "polarized" intensity distribution ('80-12-8') was more effective than "threshold training" ('65-27-8') in sub-elite runners over an 18-week period (10.4 km performance improvement of 157 vs. 121 s) (Esteve-Lanao et al., 2007). The XC training was polarized in NC athletes, but the high volume of strength-speed-jump training necessary for ski jumping performance possibly decreased the "polarization" influence (only 51% of TL at LIT). One may question if this low LIT volume would explain partly why LHTL was less effective in NC compared with XC.

The present results suggest that performing a high LIT volume is paramount during LHTL. In our view, this is particularly relevant and the "polarized" distribution is a prerequisite for inducing beneficial adaptations during altitude/hypoxic training period. It is known that training at LIT stimulates the parasympathetic branch of the neuro-vegetative system (Mourot et al., 2004). This type of training permits to avoid the onset of hypoxia-induced fatigue and is therefore effective for improving aerobic capacities and performance (Seiler et al., 2007; Schmitt et al., 2008). In NC, one may hypothesize that the pyramidal organization of the training intensities led to the observed misbalance in neuro-vegetative activity. The combination of a relative low stimulation effect of 51% of LIT on the parasympathetic activity and a high stress effect of 39% of strength-speed-jump training on the sympathetic activity could induce a fatigue effect and the subsequent decrease in specific performance reported in NC.

## Specific Performance and Lactate

The large decrease in [La-] observed only in NC (**Table 2**) suggests a large reduction in the glycolysis and glycogenosis maximal power of these subjects. The correlation ($r = -0.77$) between [La-] and time in the roller-ski test illustrates the influence of the glycolysis power in maximal endurance performance, as previously described (Urhausen and Kindermann, 2002). The [La-] decrement during maximal aerobic exercise has been shown as a marker of fatigue (Meeusen et al., 2013). It is important to observe that the XC subjects did not degrade in glycolysis maximal power despite a large

**TABLE 3 |** Heart rate and heart rate variability (HRV) parameters (in absolute and relative units) in supine (SU) and standing (ST) positions, 1 day before (Pre) and 1 day after (*Post*) live high – train low (LHTL) intervention.

| | | XC | | | NC | | |
|---|---|---|---|---|---|---|---|
| | | **Pre** | ***Post*** | ***p*** | **Pre** | ***Post*** | ***p*** |
| $HR_{SU}$ | bpm | *51.6 ± 5.7* | *54.9 ± 6.0* | *0.05* | 46.8 ± 14.6 | 46.0 ± 20.8 | 0.13 |
| | % | – | *6.9 ± 10.4* | *0.04* | – | 6.0 ± 10.9 | 0.17 |
| $HR_{ST}$ | bpm | 77.2 ± 9.7 | 81.6 ± 8.8 | 0.23 | *73.1 ± 21.5* | *72.4 ± 32.4* | *0.04* |
| | % | – | 6.2 ± 12.5 | 0.09 | – | *9.9 ± 11.6* | *0.05* |
| $LF_{SU}$ | $ms^2$ | 2726 ± 2906 | 4294 ± 3485 | 0.17 | 3493 ± 2408 | 4479 ± 4164 | 0.89 |
| | % | – | *188.0 ± 264.8* | *0.03* | – | 70.0 ± 201.6 | 0.36 |
| $LF_{ST}$ | $ms^2$ | 5602 ± 3773 | 6585 ± 4174 | 0.41 | 6555 ± 4368 | 5932 ± 5027 | 0.79 |
| | % | – | 52.7 ± 126.8 | 0.18 | – | −2.3 ± 71.0 | 0.93 |
| $HF_{SU}$ | $ms^2$ | *4981 ± 3818* | *5151 ± 3299* | *0.77* | *6212 ± 4030* | *3562 ± 2638* | *0.17#* |
| | % | – | *30.6 ± 85.8* | *0.24* | – | *−8.3 ± 129.7* | *0.86#* |
| $HF_{ST}$ | $ms^2$ | 1393 ± 2340 | 1244 ± 1703 | 0.64 | 819 ± 651 | 677 ± 515 | 0.25 |
| | % | – | 65.0 ± 171.6 | 0.22 | – | −15.0 ± 36.0 | 0.28 |
| $LF + HF_{SU}$ | $ms^2$ | 7707 ± 5905 | 9444 ± 5616 | 0.09 | 9642 ± 5535 | 7951 ± 6241 | 0.43 |
| | % | – | 61.4 ± 101.4 | 0.06 | – | 16.8 ± 149.6 | 0.76 |
| $LF + HF_{ST}$ | $ms^2$ | 6995 ± 5627 | 7829 ± 5490 | 0.51 | 7333 ± 4615 | 6580 ± 5303 | 0.77 |
| | % | – | 47.5 ± 126.6 | 0.22 | – | −3.4 ± 67.7 | 0.89 |
| $LF_{SUnu}$ | n.u. | 31.9 ± 17.3 | 44.8 ± 19.7 | 0.08 | 40.2 ± 14.9 | 47.1 ± 21.1 | 0.44 |
| | % | – | 68.1 ± 115.4 | 0.06 | – | 23.3 ± 58.5 | 0.29 |
| $LF_{STnu}$ | n.u. | 83.4 ± 12.2 | 86.6 ± 6.0 | 0.34 | 84.6 ± 23.0 | 77.5 ± 32.7 | 0.95 |
| | % | – | 5.4 ± 14.8 | 0.23 | – | −0.1 ± 2.7 | 0.95 |
| $HF_{SUnu}$ | n.u. | 68.1 ± 17.3 | 55.2 ± 19.7 | 0.08 | 54.3 ± 17.5 | 40.6 ± 18.9 | 0.44 |
| | % | – | −13.9 ± 35.5 | 0.20 | – | −5.5 ± 39.2 | 0.70 |
| $HF_{STnu}$ | n.u. | 16.6 ± 12.2 | 13.3 ± 8.0 | 0.34 | 9.1 ± 3.3 | 8.4 ± 4.1 | 0.96 |
| | % | – | 17.5 ± 111.9 | 0.59 | – | −0.1 ± 32.0 | 0.99 |
| $RMSSD_{SU}$ | ms | 108 ± 45 | 114 ± 34 | 0.49 | 115 ± 48 | 95 ± 51 | 0.31 |
| | % | – | 13.9 ± 38.2 | 0.23 | – | −9.2 ± 42.5 | 0.56 |
| $RMSSD_{ST}$ | ms | 51 ± 25 | 42 ± 26 | 0.14 | 43 ± 15 | 34 ± 16 | 0.06 |
| | % | – | −11.0 ± 38.3 | 0.34 | – | −17.3 ± 22.4 | 0.06 |

*With heart rate (HR), low (LF) and high (HF) frequency spectral power, LF and HF in normalized units (LFnu, HFnu), and square root of the mean of the sum of the squares of differences between adjacent normal R-R interval (RMSSD). XC for cross-country skiers, and NC for Nordic-combined groups. Data are reported as mean and standard deviation (SD). With $p < 0.05$ for significant difference between Pre and Post and # ($p < 0.05$), in italic, for difference of change Pre vs. Post between XC and NC.*

volume at LIT whereas at the opposite of the NC athletes who performed less LIT. One possible explanation for this could come from the autonomous fatigue induced by the combination of hypoxic exposure and the high volume of strength, speed training sessions, and jumping in the NC subjects.

## Heart Rate Variability

Training loads was similar in XC and NC in the 3 weeks preceding LHTL and similar HR and HRV parameters were observed at Pre between XC and NC groups. Despite obvious physiological differences between these two groups, one could postulate that the fitness level was satisfying for both XC and NC at the beginning of LHTL.

The QSFMS questionnaire did not identify any fatigue during LHTL in both XC and NC. However, a HRV difference was observed in HF in supine position (**Table 3**), suggesting a lesser alteration of the neuro-vegetative balance in the XC group.

The current results are in accordance with those of Seiler et al. (2007), which demonstrated that highly trained athletes performing exercise for ≤120 min below the first ventilatory threshold (VT1) showed minimal disturbance in autonomic nervous system (ANS). Particularly in HRV temporal analysis with RMSSD and in spectral analysis with HF, these authors reported that the post-exercise parasympathetic reactivation/recovery was very fast. VT1 can be considered as a "binary" threshold for recovery in elite endurance athletes (Seiler et al., 2007).

In NC, four types of fatigue (F) were statistically determined (**Figure 5**). These types of fatigue were already described on Nordic-skiers (Schmitt et al., 2015) and in a swimming Olympic champion (Schmitt et al., 2016). For one subject, the fatigue type named $F(LF_{SU}{}^{+})$ was identified with increases in supine low frequency ($LF_{SU}$) in spectral energy and in HR. This fatigue state represents a hypertonicity in sympathetic activity. The main type of fatigue $F(HF_{SU}{}^{-}\ LF_{ST}{}^{-})$ was observed in five subjects and corresponds to a decrease in LF and high (HF) frequency observed in both supine and standing positions and accompanied by an increased HR. It presents a state of hypotonicity in the

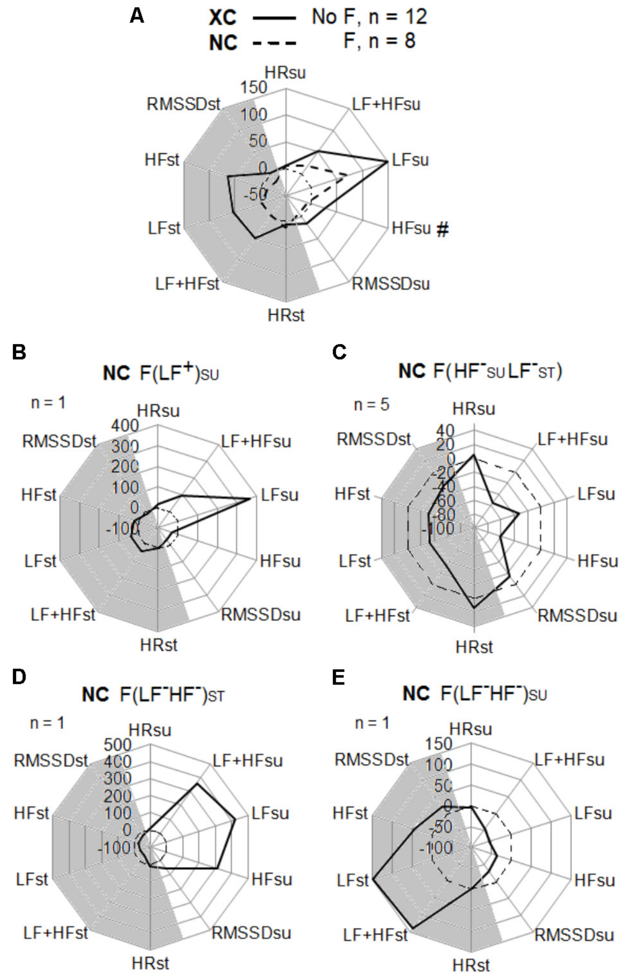


**FIGURE 5 |** Heart rate variability, and heart rate change (%) between Pre and Post tests in the cross-country skiers (XC) and the Nordic-combined (NC) groups. HRV parameters in supine (SU) and standing (ST) positions with high (HF) and low (LF) spectral frequency powers, the addition of LF + HF, the temporal analysis of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (RMSSD), and the heart rate (HR). **(A)** XC ($n$ = 12) with no fatigue (NF), and NC ($n$ = 8) with fatigue (F). Fatigue (F) types were statistically sorted in NC: **(B)** $F(LF^{+})_{SU}$ for fatigue with $LF_{SU}$ increased, **(C)** $F(HF^{-}{}_{SU}LF^{-}{}_{ST})$ for fatigue with $HF_{SU}$ and $LF_{ST}$ decreased, **(D)** $F(LF^{-}HF^{-})_{ST}$ for fatigue with $LF_{ST}$ and $HF_{ST}$ decreased, **(E)** $F(LF^{-}HF^{-})_{SU}$ for fatigue with $LF_{SU}$ and $HF_{SU}$ decreased.

two branches (sympathetic and parasympathetic) of the neuro-vegetative system. For one subject, the fatigue type named $F(LF^{-}HF^{-})_{ST}$ was characterized by a decrease in standing LF accompanied by an increase in HR. Finally for one subject, the fatigue type named $F(LF^{-}HF^{-})_{SU}$ showed decreased LF and HF only in the supine position with increased HR and is related to a parasympathetic hypotonia (Seiler et al., 2007).

One important point of the present study is that these fatigue states were systematically associated to a decreased performance observed in all NC athletes but were not diagnosed by the questionnaire. This reinforces the practical usefulness of HRV that appears very sensitive to acute onset of fatigue in endurance athletes (Schmitt et al., 2015, 2016).

## PRACTICAL APPLICATIONS

Several results of this study provide practical applications for sports coaches and researchers.

First, we confirm the effectiveness of LHTL in endurance athletes (as in the present elite *XC* skiers) as shown for 20 years in most of the existing literature (Bonetti and Hopkins, 2009; Millet et al., 2017) but also in excellent case studies (Solli et al., 2017). In addition, our results suggest that a large LIT volume is paramount during LHTL. We recommend having at least 80% of training time at LIT.

All the NC athletes reported a fatigue state at the end of LHTL. They had to perform a high percentage of strength and ski jumping training. This training in zone IV is focused on the development of force-speed and combined with a moderate volume of LIT could produce fatigue in LHTL. The present LHTL training content seems therefore less beneficial in NC athletes than in XC skiers.

Further research is needed to investigate if the addition/combination of recent hypoxic methods as resistance training in hypoxia or repeated sprint training in hypoxia (Girard et al., 2017) would be valuable in *NC athletes*.

## LIMITATIONS AND STRENGTHS

### Limitations

The main limitation concerns the design of the study. With a small number of subjects in NC (only eight subjects of the A and B French national teams), it was not statistically possible to split the group in two conditions; i.e., predominance of LIT vs. lower LIT content. Amendment of the training distribution is very difficult with elite athletes and to our knowledge there are only descriptive studies in this area with World-level athletes.

### Strengths

It is an applied study in ecological situation with "true" elite athlete; i.e., competing in European and World cups. Another strength is that the HRV fatigue states were related to the specific performance decrease. This reinforces the usefulness of monitoring different fatigue sub-categories as previously described by our research group (Schmitt et al., 2015, 2016).

## CONCLUSION

The present study showed that LHTL was beneficial in XC skiers but not in NC athletes. The training intensity distribution (i.e., ∼82% of LIT) of the XC group led to a specific (roller-ski) performance enhancement in 100% of the subjects whereas the lower LIT volume, and higher strength and speed training intensity distribution (i.e., ∼51% of LIT; ∼39% of strength and speed training) of the NC group induced an altered performance in all subjects, identified as overreached.

## AUTHOR CONTRIBUTIONS

LS and GM designed the experimental protocol. LS, SW, NC, and GM performed the data collection and analysis. LS and GM wrote the manuscript. LS, SW, NC, and GM read and approved the final manuscript.

## ACKNOWLEDGMENTS

We thank the athletes of the French national *XC* skiing (men and women) and *NC* teams, and their coaches; for *XC* skiing: Vincent Vittoz and Thibaut Chene, for *NC*: Jérôme Laheurte and Cyril Michaud-Fidey.

## REFERENCES

Akselrod, S., Gordon, D., Ubel, F. A., Shannon, D. C., Berger, A. C., and Cohen, R. J. (1981). Power spectrum analysis of heart rate fluctuation: a quantitative probe of beat-to-beat cardiovascular control. *Science* 213, 220–222. doi: 10.1126/science.6166045

Benhaddad, A., Bouix, D., Khaled, S., Micallef, J. P., Mercier, J., Bringer, J., et al. (1999). Early hemorheologic aspects of overtraining in elite athletes. *Clin. Hemorheol. Microcirc.* 20, 117–125.

Bonetti, D. L., and Hopkins, W. G. (2009). Sea-level exercise performance following adaptation to hypoxia: a meta-analysis. *Sports Med.* 39, 107–127. doi: 10.2165/00007256-200939020-00002

Esteve-Lanao, J., Foster, C., Seiler, S., and Lucia, A. (2007). Impact of training intensity distribution on performance in endurance athletes. *J. Strength Cond. Res.* 21, 943–949.

Girard, O., Brocherie, F., and Millet, G. P. (2017). Effects of altitude/hypoxia on single- and multiple-sprint performance: a comprehensive review. *Sports Med.* 47, 1931–1949. doi: 10.1007/s40279-017-0733-z

Goldstein, D. S., Bentho, O., Park, M. Y., and Sharabi, Y. (2011). Low-frequency power of heart rate variability is not a measure of cardiac sympathetic tone but may be a measure of modulation of cardiac autonomic outflows by baroreflexes. *Exp. Physiol.* 96, 1255–1261. doi: 10.1113/expphysiol.2010.056259

Harriss, D., and Atkinson, G. (2015). Ethical standards in sports and exercise science research: 2016 update. *Int. J. Sports Med.* 36, 1121–1124. doi: 10.1055/s-0035-1565186

Levine, B. D., and Stray-Gundersen, J. (1997). "Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance. *J. Appl. Physiol.* 83, 102–112. doi: 10.1152/jappl.1997.83.1.102

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., et al. (2013). Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med. Sci. Sports Exerc.* 45, 186–205. doi: 10.1249/MSS.0b013e318279a10a

Millet, G. P., Chapman, R. F., Girard, O., and Brocherie, F. (2017). Is live high-train low altitude training relevant for elite athletes? Flawed analysis from inaccurate data. *Br. J. Sports Med.* doi: 10.1136/bjsports-2017-098083 [Epub ahead of print].

Millet, G. P., Roels, B., Schmitt, L., Woorons, X., and Richalet, J. P. (2010). Combining hypoxic methods for peak performance. *Sports Med.* 40, 1–25. doi: 10.2165/11317920-000000000-00000

Mourot, L., Bouhaddi, M., Perrey, S., Rouillon, J. D., and Regnard, J. (2004). Quantitative Poincare plot analysis of heart rate variability: effect of endurance training. *Eur. J. Appl. Physiol.* 91, 79–87. doi: 10.1007/s00421-003-0917-0

Mujika, I., Busso, T., Lacoste, L., Barale, F., Geyssant, A., and Chatard, J. C. (1996). Modeled responses to training and taper in competitive swimmers. *Med. Sci. Sports Exerc.* 28, 251–258. doi: 10.1097/00005768-199602000-00015

Pomeranz, B., Macaulay, R. J., Caudill, M. A., Kutz, I., Adam, D., Gordon, D., et al. (1985). Assessment of autonomic function in humans by heart rate spectral analysis. *Am. J. Physiol.* 248, 151–153. doi: 10.1152/ajpheart.1985.248.1.H151

Reinhard, U., Muller, P. H., and Schmulling, R. M. (1979). Determination of anaerobic threshold by the ventilation equivalent in normal individuals. *Respiration* 38, 36–42. doi: 10.1159/000194056

Reyes del Paso, G. A., Langewitz, W., Mulder, L. J., Van Roon, A., and Duschek, S. (2013). The utility of low frequency heart rate variability as an index of sympathetic cardiac tone: a review with emphasis on a reanalysis of previous studies. *Psychophysiology* 50, 477–487. doi: 10.1111/psyp.12027

Sandbakk, O., Rasdal, V., Braten, S., Moen, F., and Ettema, G. (2016). How do world-class nordic combined athletes differ from specialized cross-country skiers and ski jumpers in sport-specific capacity and training characteristics? *Int. J. Sports Physiol. Perform.* 11, 899–906. doi: 10.1123/ijspp.2015-0285

Schmitt, L., Fouillot, J. P., Millet, G. P., Robach, P., Nicolet, G., Brugniaux, J., et al. (2008). Altitude, heart rate variability and aerobic capacities. *Int. J. Sports Med.* 29, 300–306. doi: 10.1055/s-2007-965355

Schmitt, L., Hellard, P., Millet, G. P., Roels, B., Richalet, J. P., and Fouillot, J. P. (2006). Heart rate variability and performance at two different altitudes in well-trained swimmers. *Int. J. Sports Med.* 27, 226–231. doi: 10.1055/s-2005-865647

Schmitt, L., Regnard, J., Auguin, D., and Millet, G. (2016). Monitoring training and fatigue status with heart rate variability: case study in a swimming Olympic champion. *J. Fit. Res.* 5, 38–45.

Schmitt, L., Regnard, J., Desmarets, M., Mauny, F., Mourot, L., Fouillot, J. P., et al. (2013). Fatigue shifts and scatters heart rate variability in elite endurance athletes. *PLoS One* 8:e71588. doi: 10.1371/journal.pone.0071588

Schmitt, L., Regnard, J., Parmentier, A. L., Mauny, F., Mourot, L., Coulmy, N., et al. (2015). Typology of "fatigue" by heart rate variability analysis in elite Nordic-skiers. *Int. J. Sports Med.* 36, 999–1007. doi: 10.1055/s-0035-1548885

Seiler, K. S., and Kjerland, G. O. (2006). Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scand. J. Med. Sci. Sports* 16, 49–56. doi: 10.1111/j.1600-0838.2004.00418.x

Seiler, S. (2010). What is best practice for training intensity and duration distribution in endurance athletes? *Int. J. Sports Physiol. Perform.* 5, 276–291. doi: 10.1123/ijspp.5.3.276

Seiler, S., Haugen, O., and Kuffel, E. (2007). Autonomic recovery after exercise in trained athletes: intensity and duration effects. *Med. Sci. Sports Exerc.* 39, 1366–1373. doi: 10.1249/mss.0b013e318060f17d

Sevre, K., Bendz, B., Hanko, E., Nakstad, A. R., Hauge, A., Kasin, J. I., et al. (2001). Reduced autonomic activity during stepwise exposure to high altitude. *Acta Physiol. Scand.* 173, 409–417. doi: 10.1046/j.1365-201X.2001.00925.x

Solli, G. S., Tonnessen, E., and Sandbakk, O. (2017). The training characteristics of the world's most successful female cross-country skier. *Front. Physiol.* 8:1069. doi: 10.3389/fphys.2017.01069

Stray-Gundersen, J., and Levine, B. D. (1999). "Living high and training low" can improve sea level performance in endurance athletes. *Br. J. Sports Med.* 33, 150–151. doi: 10.1136/bjsm.33.3.150

Task, F. (1996). Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task force of the European society of cardiology and the North American society of pacing and electrophysiology. *Eur. Heart J.* 17, 354–381. doi: 10.1093/oxfordjournals.eurheartj.a014868

Urhausen, A., and Kindermann, W. (2002). Diagnosis of overtraining: what tools do we have? *Sports Med.* 32, 95–102. doi: 10.2165/00007256-200232020-00002

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

CASE REPORT
published: 23 May 2018
doi: 10.3389/fphys.2018.00595

# Training Characteristics During Pregnancy and Postpartum in the World's Most Successful Cross Country Skier

**Guro S. Solli[1,2] and Øyvind Sandbakk[2]***

[1] Department of Sports Science and Physical Education, Nord University, Bodø, Norway, [2] Department of Neuromedicine and Movement Science, Centre for Elite Sports Research, Norwegian University of Science and Technology, Trondheim, Norway

OPEN ACCESS

**Edited by:**
Gregoire P. Millet,
Université de Lausanne, Switzerland

**Reviewed by:**
Laurent Mourot,
Université Bourgogne Franche-Comté, France
José González-Alonso,
Brunel University London, United Kingdom

***Correspondence:**
Øyvind Sandbakk
Oyvind.sandbakk@ntnu.no

**Specialty section:**
This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology

**Received:** 06 April 2018
**Accepted:** 02 May 2018
**Published:** 23 May 2018

**Citation:**
*Solli GS and Sandbakk Ø (2018) Training Characteristics During Pregnancy and Postpartum in the World's Most Successful Cross Country Skier. Front. Physiol. 9:595. doi: 10.3389/fphys.2018.00595*

This case-study investigated the training characteristics, physiological capacity, and body composition of the world's most successful cross country skier during the 40-week pregnancy, and the 61-week postpartum. Training data was systemized by training form (endurance, strength, and speed), intensity [low- (LIT), moderate- (MIT), and high-intensity training (HIT)], and mode (running, cycling, and skiing/roller skiing). The training volume [mean ± standard deviation (median)] during pregnancy was 12.9 ± 7.3(10.0) h/week in the first- (weeks 1–12), 18.3 ± 2.9(18.0) h/week in the second- (weeks 13–28), and 8.8 ± 4.4(9.6) h/week in the third trimester (weeks 29–40). Endurance training time was distributed into 10.9 ± 6.2(9.9), 15.2 ± 2.3(15.6), and 7.6 ± 3.8(7.9) LIT and 0.4 ± 0.5(0.0), 1.3 ± 0.4(1.4), and 0.7 ± 0.6(0.8) h/week MIT during the three trimesters. Only 2.2 h of HIT was performed during the entire pregnancy. During the first two trimesters, the distribution of exercise modes were approximately the same as pre-pregnancy, but the amount of running was reduced during the third trimester. Training volume during the postpartum periods 1–4 was 6.6 ± 3.8(7.1) (PP1; weeks 1–6), 14.1 ± 3.4(14.3) (PP2; weeks 7–12), 10.6 ± 3.8(10.4) (PP3; weeks 13–18), and 13.6 ± 4.1(14.5) h/week (PP4; weeks 19–24), respectively. Training during PP3 and PP4 was interfered with two fractions in the sacrum, leading to decreased amount of running and MIT/HIT, compensated by increased amounts of cycling. Thereafter, training volume progressively approached the pre-pregnancy values, being 18.0 ± 3.9(18.7) h/week during the general preparation- (weeks 25–44), 17.6 ± 4.4(17.3) h/week during the specific preparation- (weeks 45–53), and 16.9 ± 3.5(17.2) h/week during the competition period (CP; weeks 54–61) leading up to the subsequent world championship. The oxygen uptake at the estimated lactate threshold (LT) decreased to 90% of pre-pregnancy values in the second trimester, but remained to ∼100% in PP3. Body weight and fat-% was higher, while lean body mass and bone mineral density was lower after delivery compared to pre-pregnancy. These measurements gradually changed and were back to ∼pre-pregnancy values during CP. This study indicates that high-level cross country skiers can tolerate high training loads during pregnancy. Although the participant had some postpartum setbacks in her training due to fractures in the sacrum, reduced overall training load, followed by a slower progression and utilization of alternative exercise modes, led to a successful return to competitions.

**Keywords: body composition, endurance training, female athlete, parturition, delivery, physiological capacity, strength training**

## INTRODUCTION

There is an increasing number of women competing in elite sports, and many women want to resume their sporting career after giving birth. Although pregnant elite athletes undergoes the same anatomical, physiological, and biomechanical changes as non-athletes, their training load need to be balanced with the consideration to the health of their own and the fetus. In this context, an international expert committee recently reviewed the literature and provided specific exercise recommendations for elite athletes throughout pregnancy (Bo et al., 2016) and postpartum (Bo et al., 2017b). In general, physical activity and moderate exercise during pregnancy are found to be safe both for the mother and the child (Hellenes et al., 2015; Di Mascio et al., 2016), although 30–60% reduced training volumes during the third trimester has been reported in recreational and competitive runners (Potteiger et al., 1993; Bailey et al., 1998; Tenforde et al., 2015).

Intensive exercise >90% of maternal heart rate, especially during hot and humid conditions, could lead to a hypoxic situation for the fetus (Salvesen et al., 2012; Bo et al., 2016). This is also the case for intensive training at altitudes >1500–2000 m due to decreased fetal arterial oxygen saturation (Entin and Coffin, 2004). However, studies report that fetal hypoxia in connection with exercise is transient (Szymanski and Satin, 2012). Furthermore, the use of heavy strength training during pregnancy is debated. The Valsalva maneuver used during such training induces a rapid elevation of blood- and intra-abdominal pressure, which potentially could be harmful for both the fetus and the pelvic floor support (Harman et al., 1988; Palatini et al., 1989; Hartmann and Bung, 1999). However, recent studies found no deleterious effect on the pelvic floor investigating cross-fit athletes performing heavy lifts (80% of maximum) during pregnancy (Middlekauff et al., 2016). In summary, few studies have investigated the impact of strenuous endurance training and/or heavy strength training during pregnancy in elite endurance athletes (Bo et al., 2017a), and more research is needed to develop more specific recommendations for top athletes.

After giving birth, the athlete has to adjust the training to allow for full recovery and management of the new obligations with a newborn child, including breast-feeding and a potential irregular circadian rhythm (Potteiger et al., 1993). However, training after birth is relatively unexplored. A study, investigating 40 Norwegian elite athletes reported that 38% of these, compared to only 4% of non-athletes, started jogging within the first 6 weeks postpartum (Bo and Backe-Hansen, 2007). A marathon runner reported a training volume as high as 50 km during the initial week postpartum, which was progressively increased to 98 km during week 14 without any major problems (Potteiger et al., 1993). However, drainage of calcium from maternal skeleton during late pregnancy and calcium loss due to breast milk production could potentially lead to increased risk of fragility fractures during the postpartum period (Woodrow et al., 2006; Kovacs, 2011; Sanz-Salvador et al., 2015).

In a recent study, we investigated the training characteristics of the world's most successful female XC-skier (Solli et al., 2017), with a special focus on five consecutive successful seasons. Immediately after these seasons, the participant got pregnant and born a healthy child before she resumed to training and won four gold medals in the subsequent World Championship. Therefore, the main aim of this case-study was to investigate her training characteristics, physiological capacity and body composition during pregnancy and the year postpartum.

## METHODS

### Participant

The participant is the most successful competitor of all time in the winter Olympics, and competed at an international level for 15 years before getting pregnant at the age of 35. The participant is nulliparous from before, and had a singleton pregnancy. The study was evaluated by the Regional Committee for Medical and Health Research Ethics (2017/2070/REK-midt), and approved by the Norwegian Social Science Data Services (NSD). Written informed consent was obtained from the participant for the publication of this case report, which was performed according to the Helsinki declarations.

### Overall Design

This study builds on a previous longitudinal training study (Solli et al., 2017), and investigated the training and test data from conception to delivery, and the 61-week postpartum period until participation in the subsequent World Championship.

### Physiological Testing

The participant underwent physiological testing during the first- and second trimester and regularly after delivery, as specified in **Table 1**. Equipment and procedures for the physiological tests and body composition measurements are previously described (Solli et al., 2017). Because of radiation, no measurements of body composition was performed during pregnancy.

## Monitoring, Registration, and Systematization of Training

All training data was recorded daily by the participant in digital diaries designed by the Norwegian Olympic Federation, which previously has been reported to provide a valid and accurate measurement of the duration and intensity of training by XC-skiers (Sylta et al., 2014). As previously described (Solli et al., 2017), all training data was systematized by training form (endurance, strength, and speed), intensity [low- (LIT), moderate- (MIT), and high-intensity (HIT)], and specific (skiing/roller skiing) versus unspecific (running and cycling) exercise modes. The training during the 40 gestational weeks (gwk) was analyzed in the first- (Tri-1; gwk 1–12), second- (Tri-2; gwk 13–28), and third trimester (Tri-3; gwk 29–40). The 61 weeks postpartum period was analyzed in (PP1; weeks 1–6, PP2; weeks 7–12, PP3; weeks 13–18, and PP4; weeks 19–24), followed by the general preparation- (GP; weeks 25–44), specific preparation- (SP; weeks 45–53) and the competition period (CP; weeks 54–61).

Pre-pregnancy values are defined as the average training volume in the 5 years before pregnancy during each of the annual training phases, as previously described in detail (Solli et al., 2017).

## Interviews

To gather additional information, ensure compliance with the training diary commentaries, and verify the training intensity of different training sessions, semi-structured interviews were conducted regularly during the data-analysis phase of this study.

## Statistical Analyses

All data from the investigated periods are presented as mean ± standard deviation(median). Training time/sessions were divided by duration (days) of the specific phase and multiplied by seven to determine the weekly time and frequency. All analyses were carried out in Microsoft Office Excel 2016 (Microsoft, Redmond, WA, United States).

# RESULTS

## Physiological and Anthropometric Measurements

Changes in physiological and anthropometric parameters during pregnancy and postpartum are presented in **Table 1**. $VO_2$ at the estimated lactate threshold (LT) decreased to 95/94% of absolute/body-mass-normalized pre-pregnancy values in Tri-1, 93/89% in Tri-2, and then increased to 100/94% in PP2 and further to 103/98% in PP3. Lean body mass was 96% of pre-pregnancy value during PP1 and increased to 98% during PP4. Fat-% increased from pre-pregnancy to PP1 and progressively decreased to PP4 and CP. Whole body bone mineral density (BMD; g/cm$^2$) decreased to 92% of pre-pregnancy value during PP1 and further to 89% during PP3, and thereafter increased to 95–96% during GP and CP.

## Training During Pregnancy

### Training Volume

Five hundred and fifty-five hours distributed across 316 sessions was performed during the entire pregnancy. This constitutes a weekly average of ∼14 h and 8 sessions. The weekly distribution of training time is presented in **Figure 1A**. Average training volume was 12.9 ± 7.3(10.0) h/week, 18.3 ± 2.9(18.0) h/week, and 8.8 ± 4.4(9.6) h/week during Tri-1, Tri-2, and Tri-3, respectively, corresponding to 79, 86, and 48 % of the same period's pre-pregnancy training. During Tri-3, the training load was progressively reduced from 12.5 ± 3.3(12.2) h/week (weeks 29–32) to 8.4 ± 5.0(10.3) h/week (weeks 33–36) and 5.6 ± 1.4(5.8) h/week (weeks 37–40).

**TABLE 1** | Physiological characteristics of the world's most successful cross-country skier during pregnancy and postpartum.

| | Pre-pregnancy | During pregnancy | | | Postpartum period | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Tri-1 | Tri-2 | Tri-3 | PP1 | PP2 | PP3 | PP4 | GP | CP |
| Age (year) | 34.5 | 35.2 | 35.4 | 35.7 | 35.8 | 36.0 | 36.1 | 36.2 | 36.5 | 36.8 |
| Body height (cm) | 167 | 167 | 167 | 167 | 167 | 167 | 167 | 167 | 167 | 167 |
| Body mass (kg) | 64.0 | 65.2 | 67.1 | 79.0* | 69.4 | 68.1 | 67.6 | 68.5 | 68.3 | 64.6 |
| Body mass index (kg·m$^{-2}$) | 22.9 | 23.4 | 24.1 | 28.3* | 24.9 | 24.4 | 24.2 | 24.6 | 24.5 | 23.2 |
| Lean body mass (kg) | 55.0 | – | – | – | 53.0 | – | 52.1 | 54.0 | 54.5 | 55.0 |
| Lean upper body mass (kg) | 34.5 | – | – | – | 32.9 | – | 32.2 | 33.5 | 33.9 | 34.9 |
| Lean lower body mass (kg) | 17.6 | – | – | – | 17.0 | – | 16.8 | 17.4 | 17.5 | 17.1 |
| Fat % | 12.8 | – | – | – | 20.4 | – | 18.2 | 17.9 | 16.9 | 11.3 |
| Bone mineral density (g·cm$^{-2}$) | 1.298 | – | – | – | 1.199 | – | 1.154 | 1.203 | 1.237 | 1.250 |
| *Z*-score | 0.8 | – | – | – | 0.0 | – | –0.3 | 0.1 | 0.3 | 0.5 |
| $VO_2$ @LT (ml·kg$^{-1}$·min$^{-1}$) | 60.8 | 57.0 | 54.2 | – | – | 57.2 | 59.3 | – | – | 61.9# |
| $VO_2$ @LT (L·min$^{-1}$) | 3.9 | 3.7 | 3.6 | – | – | 3.9 | 4.0 | – | – | 4.0# |

*LT, estimated lactate threshold; $VO_2$ @LT oxygen uptake at the lactate threshold (running); Tri-1, first trimester; Tri-2, second trimester; Tri-3, third trimester; PP1, postpartum period one; PP2, postpartum period two; PP3, postpartum period three; PP4, postpartum period four; GP, general preparation period; CP, competition period; *the highest measured value before delivery; #values measured after the competition period.*

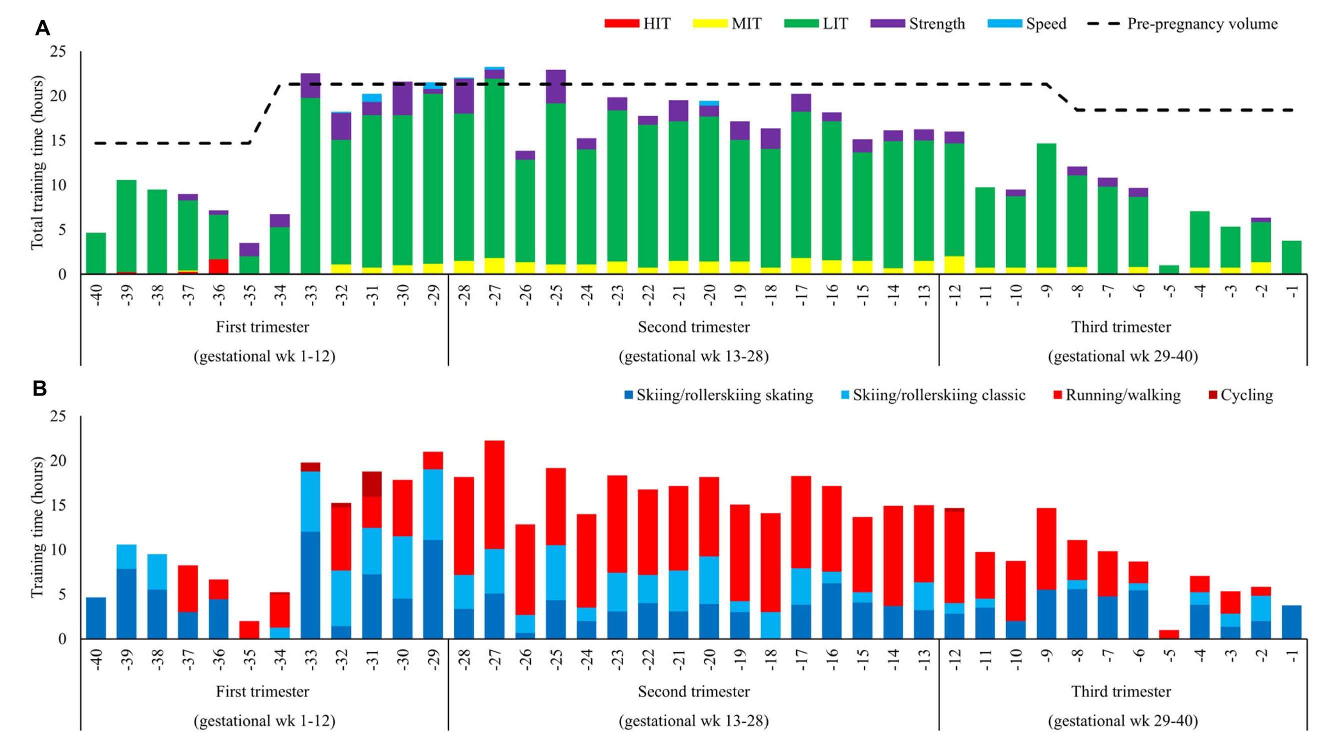


**FIGURE 1 | (A,B)** Training during 40 weeks of pregnancy **(A)** distributed into endurance (low-, moderate-, and high-intensity), strength and speed training and **(B)** distribution into specific (skiing classical or skating) and non-specific activity forms (running and cycling).

### Exercise Modes

The distribution of specific versus unspecific exercise modes is presented in **Figure 1B**. The volume of specific exercise modes was 256 h (101 h skating and 156 h classic) and 249 h was unspecific (244 h running/walking and 5 h cycling). The distribution of specific-/unspecific exercise modes was 74/26, 39/61, and 49/51% during the three trimesters. The participant stopped running during Tri-3.

### Endurance Training

Total LIT time was 465 h, distributed as 10.9 ± 6.2(9.9), 15.2 ± 2.3(15.6), and 7.6 ± 3.8(7.9) h/week during Tri-1-3, respectively. Distribution of LIT, MIT, and HIT time during the different phases is presented in **Figures 2A,B**. The number of weekly LIT session's ≥90 min was 4.3 ± 3.1(3.5), 5.4 ± 1.3(5.5), and 2.7 ± 2.2(2.5) during Tri-1-3, respectively. No session ≥150 min was performed during Tri-3. Total MIT time was 34.1 h distributed across 46 sessions during pregnancy. MIT time was 0.4 ± 0.5(0.0), 1.3 ± 0.4(1.4), and 0.7 ± 0.6(0.8) h/week during Tri-1-3, respectively. Total HIT time during pregnancy was 2.2 h, distributed across three sessions performed during the five initial weeks of Tri-1.

### Strength and Speed Training

The distribution of strength training time during the different phases is presented in **Figure 2C**. Strength training time was 1.3 ± 1.3(1.1), 1.8 ± 0.9(1.4), and 0.5 ± 0.5(0.3) h/week during Tri-1–3, respectively. The distribution of general-/heavy strength training was 59/41, 52/48, and 40/60% during Tri-1–3, respectively, with gradually more focus on the upper-body and lower focus on trunk and squat exercises. Total amount of speed training during pregnancy was 2.8 h, performed during Tri-1 and 2.

## Training During Postpartum

### Training Volume

Nine hundred and twenty-three hours distributed across 540 sessions was performed during the 61-week period after delivery until participation in the World championships. The training during this period was interfered by two bone fractions in the sacrum detected during PP3 and PP4.

Training time increased progressively from ~2 to 11 h/week during PP1. The weekly distribution of training time is presented in **Figure 3A**. Average training volume was 6.6 ± 3.8(7.1) h/week during PP1, 14.1 ± 3.4(14.3) h/week during PP2, 10.6 ± 3.8(10.4) h/week during PP3 and 13.6 ± 4.1(14.5) h/week during PP4. The training volume further increased to 18.0 ± 3.9(18.7) h/week during GP (weeks 25–44), 17.6 ± 4.4(17.3) h/week during SP (weeks 45–53) and 16.9 ± 3.5(17.2) h/week during CP (weeks 54–61), corresponding to 85, 95, and 104% of the volume in the same phases pre-pregnancy.

### Exercise Modes

The distribution of specific versus unspecific exercise modes is presented in **Figure 3B**, with a distribution of specific-/unspecific

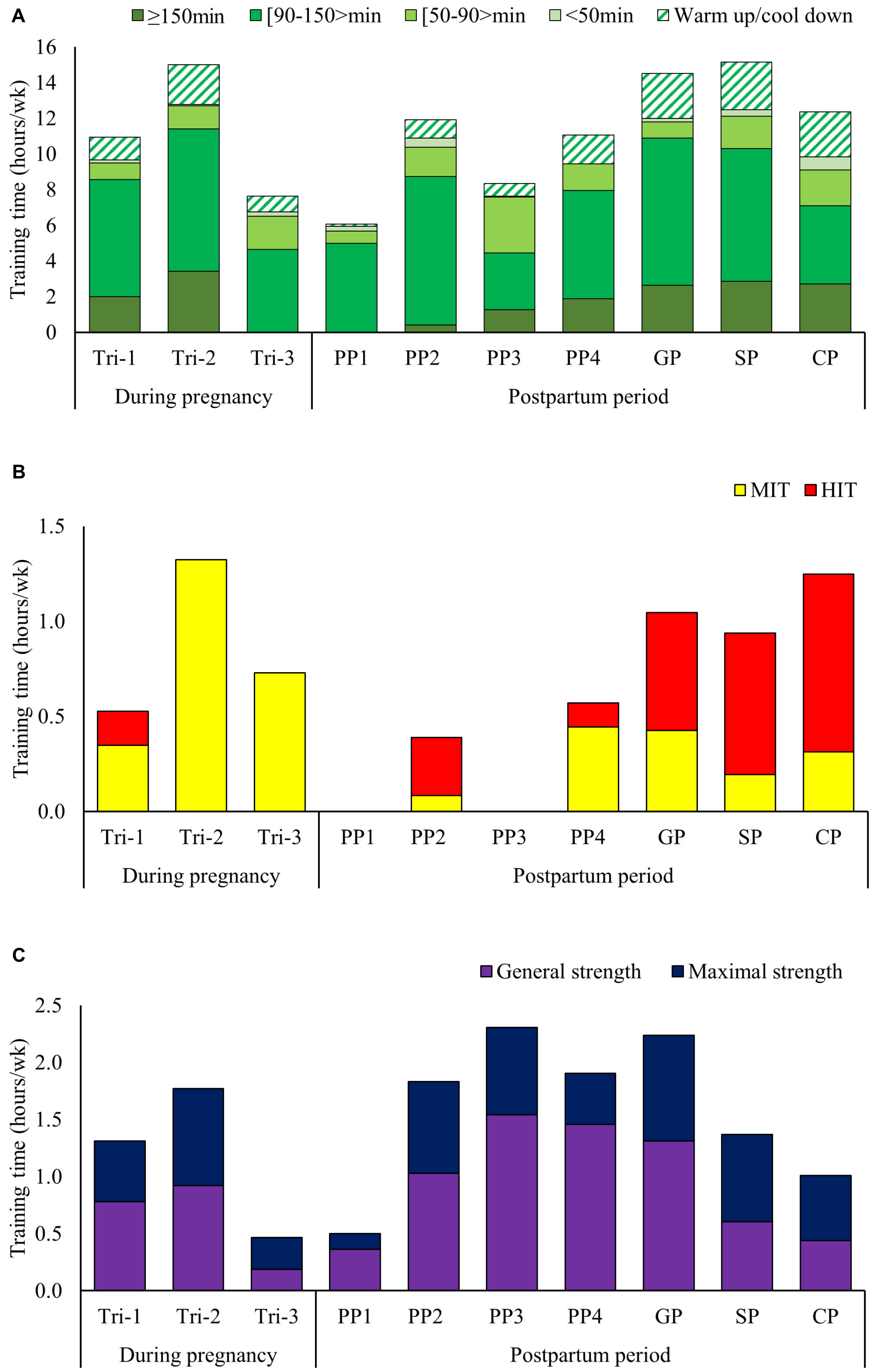


**FIGURE 2 | (A–C)** Low intensity training time categorized after duration **(A)**, distribution of moderate and high intensity training time **(B)** and distribution of general versus heavy strength training time **(C)** across the different phases of pregnancy and postpartum.

exercise modes being 85/15, 78/22, 43/56, and 69/31% during PP1-4, respectively. The amount of cycling was 3.3 ± 2.7(3.1), 2.5 ± 2.5(3.2), and 4.5 ± 4.7 (3.4) h/week during PP3, PP4, and GP, respectively. This is 3–5 times higher than pre-pregnancy values during the same phases.

## Endurance Training

Low intensity training time was distributed as 6.1 ± 3.3(6.8), 11.9 ± 3.4(10.6), 8.3 ± 3.8(8.0), and 11.1 ± 3.3(12.1) h/week during PP1-4, respectively, with the number of LIT session's ≥90 min being 2.8 ± 1.9(3.5), 4.8 ± 1.8(4.4), 2.2 ± 1.5(2.1), and

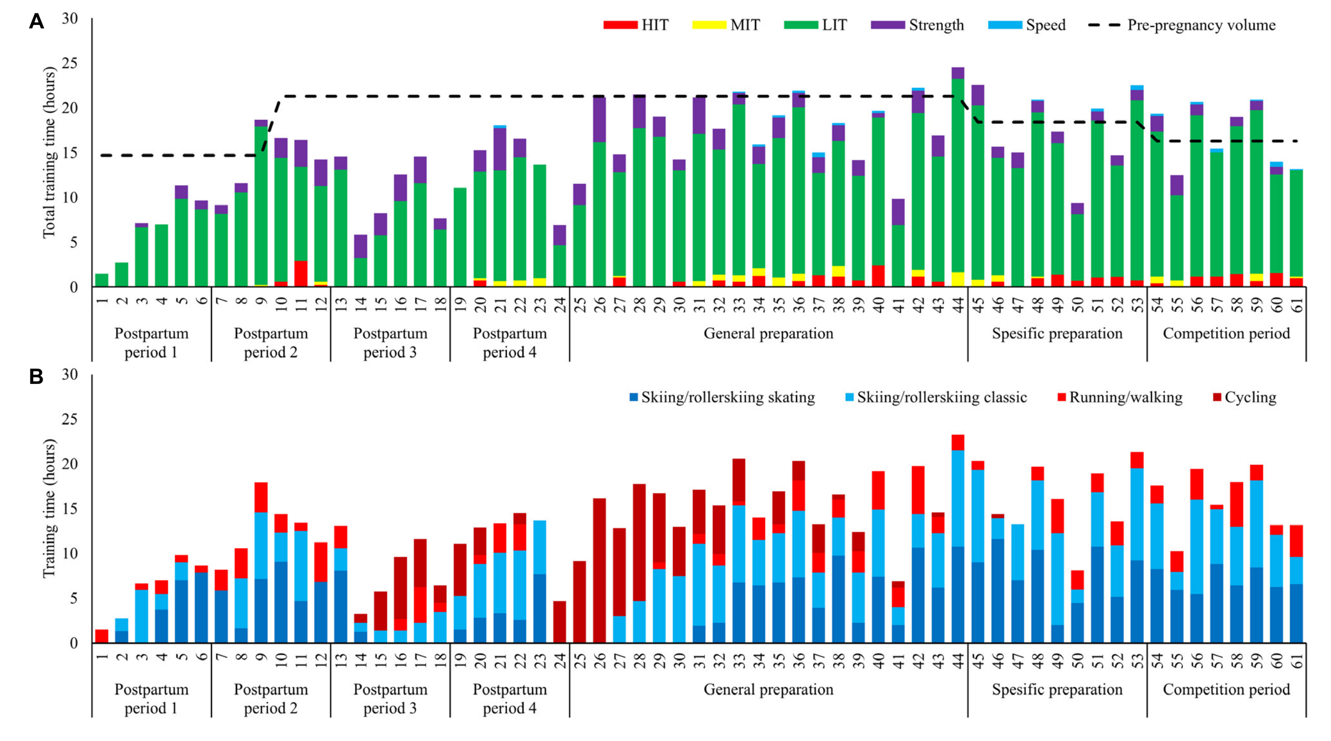


**FIGURE 3 | (A,B)** Training during 61 weeks postpartum **(A)** distributed into endurance (low-, moderate-, and high-intensity), strength and speed training and **(B)** distribution into specific (skiing classical or skating) and non-specific activity forms (running and cycling).

4.0 ± 1.1(4.0) session/week. All of the endurance training time during PP1 consisted of LIT, and the first LIT session ≥150 min was performed during PP2. MIT and HIT was re-introduced during PP2, but withdrawn during PP3 due to bone fraction, then re-introduced during PP4, but then withdrawn again with the second fraction until it was re-introduced on a permanent basis from week 30. The amount of MIT/HIT time was 0.4/0.6, 0.2/0.7, and 0.3/0.9 h/week during GP, SP, and CP.

### Strength and Speed Training

The first general strength training session was performed in week 3 and the first heavy strength session was performed during week 5. Strength training volume was 0.5 ± 0.6(0.3), 1.8 ± 1.0(1.6), 2.3 ± 0.8(2.5), and 1.9 ± 1.8(2.2) h/week during PP1-4, respectively, with the distribution of general-/heavy strength training being 72/28, 56/44, 67/33, and 77/23%. The amount of strength training was 2.2 ± 1.1(2.1), 1.4 ± 0.4(1.3), and 1.0 ± 0.8(1.0) h/week during GP, SP, and CP, respectively, corresponding to 109, 114, and 126% of pre-pregnancy values. Speed training was introduced in week 33 and thereafter employed regularly 0.1–0.2 h/week.

## DISCUSSION

In this case-study, the main aim was to investigate training characteristics, physiological capacity and body composition of the world's most successful XC-skier during the entire pregnancy, and the 61 weeks postpartum. During the first and second trimester, the average training volume was ~80–85% of pre-pregnancy values, but then progressively decreased to ~50% during the third trimester where training was gradually reduced throughout. While LIT and MIT was performed throughout pregnancy, no HIT was performed after gestational week 5 and strength training was progressively modified. In postpartum, the participant had two setbacks caused by fractures in the sacrum in PP3 and PP4. However, by reducing the overall training load, slower progression and utilization of alternative exercise modes, the participant had a successful training development and return to competition.

## Training During Pregnancy

The participant's average training volume during pregnancy was 14 h/week, which included 79, 86, and 49% of pre-pregnancy volumes during the first, second, and third trimester, respectively. The absolute volume done by our athlete is much higher than, for example, the average 8.4 h/week suggested for a rapid return to competitive sport, without jeopardizing the fetus health (Kardel, 2005). However, the relative values are more in line with marathon runners reporting average running volumes of 40 and 107 km/week during pregnancy, corresponding to ~40 and ~70% of their pre-pregnancy volume (Potteiger et al., 1993; Bailey et al., 1998). Still, this study provides the highest training volume during pregnancy ever reported in the literature. This could partly be explained by the varied exercise modes utilized in XC-skiing, e.g., allowing to reduce the mechanical stress compared to running, and partly by the high pre-pregnancy training volume and the high relative amounts during pregnancy.

The amount of HIT was substantially reduced compared to pre-pregnancy, with no HIT sessions performed after gestational week 5. This is in line with a previous study reporting that an exercise intensity >90% of maximal maternal heart rate may reduce the blood flow to the uterus and result in fetal bradycardia (Salvesen et al., 2012). In contrast, MIT was performed throughout the entire pregnancy, and with higher amounts than pre-pregnancy during the second trimester. Likely, this was an effective substitute for the reduced HIT in order to maintain performance level as high as possible during pregnancy.

During the second trimester, the athlete joined a 14-day training camp at altitude (1800 meter above sea level), and endured a training volume of ~22 h/week (i.e., 85% of pre-pregnancy altitude volumes) (Solli et al., 2017). However, only LIT and MIT was performed, and the camp was performed without any abnormalities beyond the ability to keep the same training speed as before pregnancy. Because of a possible reduction in the fetus oxygen saturation, intensive training at altitude is not recommended during pregnancy (Entin and Coffin, 2004). However, since XC-skiers normally has a lower proportion of HIT during altitude (Sandbakk and Holmberg, 2017), the participant could follow approximately the same training plan as her team mates.

The relative utilization of exercise modes was approximately the same compared to pre-pregnancy during the first and second trimester, but the amount of running was reduced during the third trimester. Specifically, our participant reported increased soreness in the muscles around her hip after running sessions during the third trimester, and stopped running approximately 6 weeks before giving birth. This is in line with previous studies (Tenforde et al., 2015), and is likely caused by the increased body weight and the changes in biomechanical stress as the gravity center alters during pregnancy.

Both general and heavy strength training was performed throughout the whole pregnancy, but with a clear volume-reduction during the third trimester. In addition, the strength training program was gradually modified, e.g., with more focus on upper-body exercises and less focus on abdominal muscles and squats. This is in line with previous reports in recreational athletes where low-resistance strength training has shown no negative effects for the fetus (Avery et al., 1999), and no negative effect on the pelvic floor was reported in cross-fit athletes performing heavy lifts during pregnancy (Middlekauff et al., 2016). In any case, the modification in strength training might have contributed to the small decline (4%) in lean body mass during pregnancy. However, more research concerning both the load and types of exercise (e.g., upper vs. lower-body muscles), and the subsequent effects on maintenance of muscle mass, is needed to give more accurate recommendations to elite athletes.

## Training During Postpartum

The participant had a quick return to training, and progressively increased training volume to 11 h/week during PP1. In PP2, this was further increased to 19 h/week and MIT and HIT was reintroduced. Strength training was included from week 3, and progressively increased to 2 h/week during PP2. However, coinciding this rapid increase in training load a fracture in the sacrum was detected during PP3. This subsequently led to a reduction in the training volume, followed by a new progression in the training during PP4, until a new fracture on the other side of the sacrum was detected. Although similar progression of training load during postpartum, without injuries, has previously been reported in a marathon runner (Potteiger et al., 1993), it is likely that these injuries occurred because of a too rapid progression. In this connection, a decrease in the BMD after delivery and further lowering to PP3 was observed. The reason for this might be that the fetal skeleton requires a substantial transfer of calcium during Tri-3 and, in addition, loss of calcium in breast milk (Sanz-Salvador et al., 2015). Currently, the mechanisms behind calcium transfer and bone turnover during pregnancy and lactating are only partly understood and there is a lack of knowledge considering the effect of exercise on these factors. However, it is likely that pregnancy is a vulnerable period for the mother's bones that especially elite athletes should be aware of.

After the second fraction, the amount of MIT and HIT was reduced and running was replaced with cycling during the following 7 weeks. At the end of GP, MIT, and HIT was reintroduced on a permanent basis and the participant immediately responded positively and gained a substantial performance improvement. In the final weeks of GP she participated at her first altitude camp after delivery, and experienced that the training during altitude was easier than pre-pregnancy. In SP the training volumes was back at pre-pregnancy levels. During CP, she followed the same tapering pattern as before pregnancy (Solli et al., 2017), but with more day-to-day adjustments of training due to the new obligations with a newborn child and more pronounced reduction of her training during the two final weeks before the successful World Championship in Lahti 2017.

## Ethical Considerations and Practical Recommendations

The following factors should be considered when implementing the findings of this study to other athletes/sports:

- *Maternal age* > 35 years is associated with several pregnancy complications (Lean et al., 2017).
- *A larger number of pregnancies and deliveries* could likely influence risks associated pregnancy.
- The *pre-pregnancy training volume* of the participant was high due to progressive increase in training volume over many years (Solli et al., 2017).
- The *characteristics of XC- skiing where* several exercise modes is utilized in training (i.e., skiing, roller-skiing, running, and cycling), which makes utilization of alternative exercise modes easier.
- Requirements of *hydration and nutrition* increases during pregnancy (Bo et al., 2016), an aspect carefully taken care of in this case.

- The *supporting network* closely supervised our participant, which is not necessarily the case for athletes at lower performance levels.

## CONCLUSION

This study provides unique data of the training characteristics, physiological capacity and body composition for the world's most successful XC-skier during pregnancy and the year postpartum. Our data indicates that high level XC-skiers can tolerate high training loads during pregnancy. However, elimination of HIT, modified strength training and a gradually reduced training load during the third trimester seems to be required. In postpartum, the setbacks in our participant's training, due to fractures in the sacrum, was likely caused by a too rapid progression of training. However, by reducing the overall training load, followed by slower progression and utilization of alternative exercise modes, the participant had a successful return to competitions and managed to win four gold medals in the subsequent World Championship.

## AUTHOR CONTRIBUTIONS

GS performed data collection and performed data and statistical analysis. GS and ØS designed the study, contributed to interpretation of the results, wrote the draft manuscript, and contributed to the final manuscript.

## ACKNOWLEDGMENTS

The authors sincerely thank Marit Bjørgen, for sharing her experiences and training data. In addition, they thank Jacob Andre Lindkvist for his help with the systematization of data, and Kirsti Krohn Garnes for helpful feedback on the manuscript.

## REFERENCES

Avery, N. D., Stocking, K. D., Tranmer, J. E., Davies, G. A., and Wolfe, L. A. (1999). Fetal responses to maternal strength conditioning exercises in late gestation. *Can. J. Appl. Physiol.* 24, 362–376. doi: 10.1139/h99-028

Bailey, D. M., Davies, B., Budgett, R., Sanderson, D. C., and Griffin, D. (1998). Endurance training during a twin pregnancy in a marathon runner. *Lancet* 351:1182. doi: 10.1016/S0140-6736(05)79128-5

Bo, K., Artal, R., Barakat, R., Brown, W., Davies, G. A., Dooley, M., et al. (2016). Exercise and pregnancy in recreational and elite athletes: 2016 evidence summary from the IOC expert group meeting, Lausanne. Part 1-exercise in women planning pregnancy and those who are pregnant. *Br. J. Sports Med.* 50, 571–589. doi: 10.1136/bjsports-2016-096218

Bo, K., Artal, R., Barakat, R., Brown, W. J., Davies, G. A. L., Dooley, M., et al. (2017a). Exercise and pregnancy in recreational and elite athletes: 2016/17 evidence summary from the IOC expert group meeting, Lausanne. Part 4-Recommendations for future research. *Br. J. Sports Med.* 51, 1724–1726. doi: 10.1136/bjsports-2017-098387

Bo, K., Artal, R., Barakat, R., Brown, W. J., Davies, G. A. L., Dooley, M., et al. (2017b). Exercise and pregnancy in recreational and elite athletes: 2016/17 evidence summary from the IOC Expert Group Meeting, Lausanne. Part 3-exercise in the postpartum period. *Br. J. Sports Med.* 51, 1516–1525. doi: 10.1136/bjsports-2017-097964

Bo, K., and Backe-Hansen, K. L. (2007). Do elite athletes experience low back, pelvic girdle and pelvic floor complaints during and after pregnancy? *Scand. J. Med. Sci. Sports* 17, 480–487. doi: 10.1111/j.1600-0838.2006.00599.x

Di Mascio, D., Magro-Malosso, E. R., Saccone, G., Marhefka, G. D., and Berghella, V. (2016). Exercise during pregnancy in normal-weight women and risk of preterm birth: a systematic review and meta-analysis of randomized controlled trials. *Am. J. Obstet. Gynecol.* 215, 561–571. doi: 10.1016/j.ajog.2016.06.014

Entin, P. L., and Coffin, L. (2004). Physiological basis for recommendations regarding exercise during pregnancy at high altitude. *High Alt. Med. Biol.* 5, 321–334. doi: 10.1089/ham.2004.5.321

Harman, E. A., Frykman, P. N., Clagett, E. R., and Kraemer, W. J. (1988). Intra-abdominal and intra-thoracic pressures during lifting and jumping. *Med. Sci. Sports Exerc.* 20, 195–201. doi: 10.1249/00005768-198820020-00015

Hartmann, S., and Bung, P. (1999). Physical exercise during pregnancy–physiological considerations and recommendations. *J. Perinat. Med.* 27, 204–215. doi: 10.1515/JPM.1999.029

Hellenes, O. M., Vik, T., Lohaugen, G. C., Salvesen, K. A., Stafne, S. N., Morkved, S., et al. (2015). Regular moderate exercise during pregnancy does not have an adverse effect on the neurodevelopment of the child. *Acta Paediatr.* 104, 285–291. doi: 10.1111/apa.12890

Kardel, K. R. (2005). Effects of intense training during and after pregnancy in top-level athletes. *Scand. J. Med. Sci. Sports* 15, 79–86. doi: 10.1111/j.1600-0838.2004.00426.x

Kovacs, C. S. (2011). Calcium and bone metabolism disorders during pregnancy and lactation. *Endocrinol. Metab. Clin. North Am.* 40, 795–826. doi: 10.1016/j.ecl.2011.08.002

Lean, S. C., Derricott, H., Jones, R. L., and Heazell, A. E. P. (2017). Advanced maternal age and adverse pregnancy outcomes: a systematic review and meta-analysis. *PLoS One* 12:e0186287. doi: 10.1371/journal.pone.0186287

Middlekauff, M. L., Egger, M. J., Nygaard, I. E., and Shaw, J. M. (2016). The impact of acute and chronic strenuous exercise on pelvic floor muscle strength and support in nulliparous healthy women. *Am. J. Obstet. Gynecol.* 215, 316.e1–316.e7. doi: 10.1016/j.ajog.2016.02.031

Palatini, P., Mos, L., Munari, L., Valle, F., Del Torre, M., Rossi, A., et al. (1989). Blood pressure changes during heavy-resistance exercise. *J. Hypertens. Suppl.* 7, S72–S73. doi: 10.1097/00004872-198900076-00032

Potteiger, J. A., Welch, J. C., and Byrne, J. C. (1993). From parturition to marathon: a 16-wk study of an elite runner. *Med. Sci. Sports Exerc.* 25, 673–677. doi: 10.1249/00005768-199306000-00004

Salvesen, K. A., Hem, E., and Sundgot-Borgen, J. (2012). Fetal wellbeing may be compromised during strenuous exercise among pregnant elite athletes. *Br. J. Sports Med.* 46, 279–283. doi: 10.1136/bjsm.2010.080259

Sandbakk, O., and Holmberg, H. C. (2017). Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int. J. Sports Physiol. Perform.* 12, 1003–1011. doi: 10.1123/ijspp.2016-0749

Sanz-Salvador, L., Garcia-Perez, M. A., Tarin, J. J., and Cano, A. (2015). Bone metabolic changes during pregnancy: a period of vulnerability to osteoporosis and fracture. *Eur. J. Endocrinol.* 172, R53–R65. doi: 10.1530/EJE-14-0424

Solli, G. S., Tonnessen, E., and Sandbakk, O. (2017). The training characteristics of the world's most successful female cross-country skier. *Front. Physiol.* 8:1069. doi: 10.3389/fphys.2017.01069

Sylta, O., Tonnessen, E., and Seiler, S. (2014). Do elite endurance athletes report their training accurately? *Int. J. Sports Physiol. Perform.* 9, 85–92. doi: 10.1123/ijspp.2013-0203

Szymanski, L. M., and Satin, A. J. (2012). Strenuous exercise during pregnancy: is there a limit? *Am. J. Obstet. Gynecol.* 207, 179.e1–179.e6. doi: 10.1016/j.ajog.2012.07.021

Tenforde, A. S., Toth, K. E., Langen, E., Fredericson, M., and Sainani, K. L. (2015). Running habits of competitive runners during pregnancy and breastfeeding. *Sports Health* 7, 172–176. doi: 10.1177/1941738114549542

Woodrow, J. P., Sharpe, C. J., Fudge, N. J., Hoff, A. O., Gagel, R. F., and Kovacs, C. S. (2006). Calcitonin plays a critical role in regulating skeletal mineral metabolism during lactation. *Endocrinology* 147, 4010–4021. doi: 10.1210/en.2005-1616

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

PERSPECTIVE
published: 21 December 2018
doi: 10.3389/fphys.2018.01772

# The Training of Olympic Alpine Ski Racers

*Matthias Gilgien[1,2]*, Robert Reid[2], Christian Raschner[3], Matej Supej[4] and Hans-Christer Holmberg[5,6,7]*

[1] Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway, [2] Alpine Skiing, Norwegian Ski Federation, Oslo, Norway, [3] Department of Sport Science, Olympic Training Center, University of Innsbruck, Innsbruck, Austria, [4] Laboratory of Biomechanics, Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia, [5] Swedish Winter Sports Research Centre, Mid Sweden University, Östersund, Sweden, [6] School of Sport Sciences, UiT The Arctic University of Norway, Tromsø, Norway, [7] School of Kinesiology, University of British Columbia, Vancouver, BC, Canada

OPEN ACCESS

**Edited by:**
Nicolas Coulmy,
Fédération Française de Ski, France

**Reviewed by:**
Andreas Huber,
Olympiastützpunkt Bayern, Germany
David Bacharach,
St. Cloud State University,
United States

***Correspondence:**
Matthias Gilgien
matthias.gilgien@nih.no

**Specialty section:**
This article was submitted to
Exercise Physiology,
a section of the journal
Frontiers in Physiology

**Received:** 29 June 2018
**Accepted:** 23 November 2018
**Published:** 21 December 2018

**Citation:**
Gilgien M, Reid R, Raschner C, Supej M and Holmberg H-C (2018) The Training of Olympic Alpine Ski Racers. Front. Physiol. 9:1772. doi: 10.3389/fphys.2018.01772

Alpine combined was the only alpine ski racing event at the first Winter Olympic Games in 1936, but since then, slalom, giant slalom, super-G, downhill, and team events have also become Olympic events. Substantial improvements in slope preparation, design of courses, equipment, and the skills of Olympic alpine skiers have all helped this sport attain its present significance. Improved snow preparation has resulted in harder surfaces and improved equipment allows a more direct interaction between the skier and snow. At the same time, courses have become more challenging, with technical disciplines requiring more pronounced patterns of loading – unloading, with greater ground reaction forces. Athletes have adapted their training to meet these new demands, but little is presently known about these adaptations. Here, we describe how Olympic athletes from four of the major alpine ski racing nations prepared for the Olympic Games in South Korea in 2018. This overview describes their typical exercise programs with respect to physical conditioning, ski training and periodization, based on interviews with the coaching staff. Alpine ski racing requires mastery of a broad spectrum of physical, technical, mental, and social skills. We describe how athletes and teams deal with the multifactorial nature of the training required. Special emphasis is placed on sport-specific aspects, such as the combination of stimuli that interfere with training, training with chronic injury, training at altitude and in cold regions, the efficiency and effectiveness of ski training and testing, logistic challenges and their effects on fatigue, including the stress of frequent traveling. Our overall goal was to present as complete a picture of the training undertaken by Olympic alpine skiers as possible and on the basis of these findings propose how training for alpine ski racing might be improved.

**Keywords: snow sport, elite, performance, physical demands, physical conditioning, periodization, injury, health**

## INTRODUCTION

Alpine racing consists of four primary ski disciplines (events), which vary in duration, number of changes in direction, course, terrain, and jumps. The duration of a single run and the average and maximal (avg./max) speed for the primary events are as follows: slalom (SL, 52 s, 54 km/h), giant slalom (GS, 77 s, 65/85 km/h), Super-G (SG, 93 s, 86/110 km/h), and downhill (DH, 121 s, 94/150 km/h) (Reid, 2010; Gilgien et al., 2014, 2015a,b).

Alpine ski racing is a technical sport, placing high demands on the athlete's skill and motor control (Raschner et al., 2017). Although external conditions do not change suddenly and unexpectedly, the technique involved is similar to that of open motor skill sports due to the extremely high variability in these conditions. Variations in course setting, terrain, snow conditions, speed, and visibility all place very high demands on the skier's ability to adapt technique and tactics effectively. Furthermore, when competing, the athlete must be prepared for situations with limited knowledge of the speed at which they will approach, how their equipment will interact with the snow surface, and whether this surface has changed since the course was inspected (Reid, 2000). These considerations have important implications for how Olympic skiers should train technique in order to be prepared for competition.

In addition to technique, alpine ski racing challenges virtually all of an athlete's physical capacities, including strength (maximal strength, strength endurance, and stability), power, aerobic and anaerobic capacity, balance, coordination and motor control, and mobility (Neumayr et al., 2003; Maffiuletti et al., 2006; Hydren et al., 2013; Polat, 2016; Gilgien et al., 2018). At the same time, these challenges are not extreme in terms of human capacity (Turnbull et al., 2009) and athletes with substantially different physical characteristics can all compete at a high level.

Surprisingly, the training required by Olympic alpine ski racers has received little attention from researchers (Hydren et al., 2013). Therefore, we asked (open interview with 10 initial questions) four members of the coaching staff (head coaches and coach/scientists with access to training records of the different training groups within the ski federations working with Olympic racers in Germany, Norway, Sweden and Switzerland to describe the nature and volume of their training with respect to ski training and physical conditioning, periodization and sport-specific challenges. Ethical considerations regarding voluntary participation of the coaching stuff, confidentiality, and anonymity were strictly followed. The information thus collected was used to arrive at generalizations concerning this training and establishing the correct order of magnitude of their training. Factors of specific relevance to Olympic ski racers are highlighted to provide insight into real-life Olympic training. Our manuscript is a first attempt to provide researchers with a holistic understanding of training, as well as the related constraints and challenges. An improved understanding has the potential to better design relevant training-related research projects related to the real-life situation of alpine ski racing. However, the accuracy of the data collected in the teams did not allow valid comparisons between women and men or elaboration on what nations should enhance in order to improve performance.

## SKI TRAINING

Olympic alpine skiers typically train and compete for 130–150 days each year. The total volume of training and its distribution between the four disciplines depends on the skier's specialization. Most Olympic skiers specialize either in the technical (SL and GS) or speed disciplines (SG and DH), although single-discipline specialists and athletes competing in 3 or more disciplines are not uncommon. While the majority of an athlete's training involves his/her own discipline, Olympic skiers sometimes train other disciplines as well. For example, speed discipline specialists may train some SL to prepare for the combined event, and vice-versa. The recent addition of parallel SL events to the World Cup and Olympic Games has increased focus on this discipline. However, regardless of specialization, the total number of training days appears to be similar.

**Table 1** documents typical skiing training volumes for Olympic alpine skiers. Part 1 provides examples of sessions during the preparation and competition periods for each discipline, while Parts 2 and 3 illustrate the training by an athlete who trains either two technical or two speed disciplines for an equal number of days each. The volume of competition-like training is presented both in terms of time and number of turns (excluding warm-ups, skiing to and from lifts, and the time spent on lifts).

An on-snow training session is commonly held in the morning, when the temperature is low and snow hard. Such a session begins with an off-snow warm-up and 2–5 warm-up runs of free-skiing, including technique drills, on a prepared slope. Most of the session involves partial or full-length runs on a competition-like course, with the number of runs and type of course set depending on the event and time of year (**Table 1**). Breaks between runs are typically 10–30 min long, depending to a large degree on the turn-around time on the lift. In some cases, snowmobiles are used to reduce this turn-around time.

The length and number of runs can vary substantially, depending on the season, conditions and athlete, as shown in **Table 1**. Training runs are usually shorter than competition runs for two reasons. First, full-length competition runs are quite exhausting and a larger number of shorter runs is thought to provide overall higher quality training. In addition, during training teams usually do not have access to slopes that can accommodate a full-length competition course, especially in the case of the speed disciplines and GS. Other important concerns include how best to organize training to achieve optimal conditions with respect to snow, weather and slope and, during the competition period, to achieve training conditions as similar as possible as those in the next race.

Depending on the time of year, SL training consists of 2–12 runs with 40–60 turns (each lasting about 0.8 s) for a total of 100–700 changes in direction during a session. Each of these changes involves a sharp increase in ground reaction force, which can be as high as 4 times body weight (BW) (Reid, 2010; Supej and Holmberg, 2010). GS training consists of 2–12 runs with 25–50 turns (each lasting about 1.4 s) resulting in a total of 50–600 changes in direction, each involving maximal ground reaction forces of approximately 3.2 times BW (Gilgien et al., 2014, 2018).

Depending on the time of year, SG training consists of 2–8 runs with 15–40 turns (each lasting about 2.3 s) resulting

**TABLE 1 |** Typical volumes of ski training by Olympic alpine skiers.

| | **Part 1: The content of one session of ski training during the preparation and competition periods** | ***Preparation period*** | ***Competition period*** |
|---|---|---|---|
| | *Slalom* | 6–12 runs on a partial-to-full length course × 40–60 turns | 2–6 runs on a partial-to-full length course × 50–60 turns |
| | *Giant slalom* | 6–12 runs on a partial-to-full length course × 25–50 turns | 2–5 runs on a partial-to-full length course × 25–50 turns |
| | *Super-G* | 4–8 runs on a partial-to-full length course × 15–40 turns | 2–4 runs on a partial-to-full length course × 15–40 turns |
| | *Downhill* | 4–8 runs × 15–35 turns | 3–6 runs × 15–35 turns |

| | **Part 2: Ski training during one session/period/year in terms of time** | ***Specialist technical events*** | | ***Specialist speed events*** | |
|---|---|---|---|---|---|
| | ***Event*** | ***SL*** | ***GS*** | ***SG*** | ***DH*** |
| Preparation period | *Training Days/Period* | 32 | 35 | 22 | 25 |
| | *Runs/Day* | 8 | 8 | 6 | 6 |
| | *Time/Run [s]* | 40 | 45 | 50 | 60 |
| | *Time/Day [min]* | 5.3 | 6.0 | 5.0 | 6.0 |
| | *Total Time/Event [h]* | 2.8 | 3.5 | 1.8 | 2.5 |
| | *Total Time/Period [h]* | 6.3 | | 4.3 | |
| Competition period | *Days/Period* | 30 | 32 | 25 | 32 |
| | *Runs/Day* | 4 | 3.5 | 3 | 3 |
| | *Time/Run [s]* | 40 | 45 | 50 | 60 |
| | *Time/Day [min]* | 2.7 | 2.6 | 2.5 | 3.0 |
| | *Total Time/Event [h]* | 1.3 | 1.4 | 1.0 | 1.6 |
| | *Total Time/Period [h]* | 2.7 | | 2.6 | |
| | *Total Time/Event [h]* | 4.2 | 4.9 | 2.9 | 4.1 |
| | *Total Time/Year [h]* | 9.1 | | 7.0 | |

| | **Part 3: Ski training during one session/period/year in terms of the numbers of turns** | ***Specialist technical events*** | | ***Specialist speed events*** | |
|---|---|---|---|---|---|
| | ***Event*** | ***SL*** | ***GS*** | ***SG*** | ***DH*** |
| Preparation period | *Training Days/Period* | 32 | 35 | 22 | 25 |
| | *Runs/Day* | 8 | 8 | 6 | |
| | *Turns/Run* | 50 | 37 | 28 | |
| | *Turns/Day* | 400 | 296 | 165 | |
| | *Total Turns/Event* | 12800 | 10360 | 3630 | |
| | *Total Turns/Period* | 23160 | | | |
| Competition period | *Training Days/Period* | 30 | 32 | 25 | 32 |
| | *Runs/Day* | 4 | 3.5 | 3 | 3 |
| | *Turns/Run* | 55 | 37 | 28 | |
| | *Turns/Day* | 220 | 130 | 83 | |
| | *Total Turns/Event* | 6600 | 4144 | 2063 | |
| | *Total Turns/Period* | 10744 | | | |
| Total Turns/Event/Year | | 19400 | 14504 | 5693 | |
| Total Turns/Year | | 33904 | | | |

*The ranges presented are averaged range limits (rounded-off) for the nations included. Part 1: Typical sessions of ski training for each discipline during the preparation and competition periods. Parts 2 (time) and 3 (number of competition-like turns): training by an athlete who trains for either two technical or two speed disciplines. The preparation period includes all ski training from mid-March to mid-October/mid-November and the competition period both competition and training, in both cases excluding free-skiing and any skiing that does not resemble competition.*

in a total of 30–300 changes in direction per session. Each of these changes involves a relatively smooth increase in ground reaction force compared to GS and SL, peaking at approximately 2.6 times BW (Gilgien et al., 2014, 2018). In the case of SG about 20% of the run time is spent skiing straight, without turns (Gilgien et al., 2018).

Depending on the time of year, DH training consists of 3–8 runs, with 55% of the run time spent turning (15–35 turns). Each turn lasts approximately 2.3 s, with maximal ground reaction forces of 2.6 times BW (Gilgien et al., 2014, 2018). The remaining 45% of the run time involves skiing straight, with the skier in the tucked position on average 36.8% of the time (Gilgien et al., 2018).

## PHYSICAL CONDITIONING

To meet the broad physical demands of their sport, alpine skiers train strength and core stability, power, aerobic and anaerobic endurance, coordination/motor skills, balance, and mobility, together with supplementary training, often involving cross-training in other sports (Reid, 2000; Hydren et al., 2013). Strength training often targets the entire body, with special emphasis on the legs, core, and hip/gluteal region. Depending on the athlete's individual needs, strength training can focus on strength endurance, hypertrophy, maximal strength and/or power. Compared to other sports, there is special focus on stabilization of the core and hip/pelvis region (Hydren et al., 2013), as well as eccentric training to sustain the high loads and shocks encountered when turning (Ferguson, 2010; Hydren et al., 2013; Patterson and Raschner, 2015). Training of coordination/motor control, balance and quickness involves off-snow imitation of skiing and is often combined with strength, power, or endurance training (Raschner et al., 2004; Hydren et al., 2013). The large variety of activities used for endurance training include cycling, running (on uneven terrain as well), swimming, kayaking, roller blading, and sports with intense activity such as football, hockey, and maneuvering through obstacle courses.

Within this framework, the training of Olympic skiers is adjusted to meet individual needs. The physical conditioning of specialists in technical and speed disciplines is generally similar, except that speed skiers place more emphasis on endurance and strength, while technical specialists focus on quickness and power.

During periods of physical conditioning, weekly training typically consists of 14–21 h distributed over 10–14 sessions, with a variety of training forms (**Table 2**). The nature of this training can vary substantially, since many Olympic skiers suffer acute or chronic injuries (Haaland et al., 2015), which require alternative training forms and continuous monitoring by health care personnel. Efficient and effective management of training is based on testing and analysis of individual fitness (Patterson et al., 2009, 2014; Hydren et al., 2013; Raschner et al., 2013). In the case of Olympic ski racers this is generally done twice annually, once at the beginning of the preparation period in May and again before the competition season in October. This assessment typically covers various aspects of strength, power, endurance and agility, although some nations have specific test protocols and tend to base their training more extensively on physiological testing than others. Moreover, at the highest level of performance individual differences are given great consideration when deciding when and how the skiers train, including the injuries that are not uncommon among elite skiers.

**TABLE 2 |** The nature and number of weekly sessions of physical conditioning and on-snow training an athlete can choose from during the preparation period and competition week.

Preparation period; Physical conditioning: A typical week of training is composed of the training forms listed below. Altogether, skiers perform 10–14 training sessions for a total of 14–21 h

- 2–4 sessions of endurance training (aerobic and/or anaerobic, depending on the period)
- 2–4 sessions of strength training
- 1–2 sessions of explosive strength training/plyometrics (depending on the period)
- 2–3 sessions of agility/motor training
- 3–5 sessions of stability and mobility training
- 1–2 sessions of cross-training in other sports (depending on the period) or team-building activities

Preparation period; On-snow training: A typical week of training is composed of the training forms listed below. Altogether, the skiers perform 10–14 training sessions for a total of 14–21 h

- 5–9 sessions of on-snow/technique training
- 3–7 (daily) sessions of active recovery
- 1–2 sessions of aerobic capacity (intervals)
- 0–1 session of maximal/explosive lower-body strength training
- 0–1 session of cross-training in other sports or team-building activities
- 2–7 (daily) sessions of stability and mobility training

Competition period: normally with 1–3 competitions a week. A typical week of training and competition is composed of the training forms listed below. Altogether, the skiers train/compete 7–14 times a week

- 1–3 competitions
- 1–3 official DH training runs for skiers in speed events or 1–3 ski training sessions for the other events
- 4–7 sessions of active recovery
- 4–7 sessions of stability and mobility training
- 0–1 session of aerobic capacity (intervals)
- 0–1 session of maximal/explosive lower-body strength training
- 0–1 session of speed/quickness training or games
- 1–3 days of travel (representing a significant load during this period)

## PERIODIZATION – STRUCTURE OF THE TRAINING YEAR

The periodization of alpine ski racing does not adhere strictly to a traditional annual cycle based on the schedule of competition and development of the athlete's form (Matveyev, 1981). Instead, the availability of good training conditions largely determines this periodization. The competition period lasts from October/November to March. The preparation period starts in April with on-snow ski training, followed by physical conditioning from May to July, which is then mixed with blocks of on-snow training from August to October/November. Instead of planning a single transition period following the competitive season, periods of recovery are incorporated into the program in April, May, and July.

## THE PREPARATION PERIOD

In April, once the tourist season has abated and public slopes become more accessible for training, skiers take advantage of the remaining natural and man-made snow to test their equipment and train basic skills. The moderate altitudes and short lift turn-around times permit a relatively high volume of training.

From the middle of May to July, the northern hemisphere is often warm, limiting the possibility for high-quality training on snow. At the same time, slope availability in the southern hemisphere is limited. Therefore, this period is typically used for sustained physical conditioning designed to achieve a lasting effect. All components of conditioning are included throughout this preparation period, but initially, emphasis is placed on general physical conditioning, including strength and endurance. As summer approaches, the focus shifts to more training of maximal strength, power, and anaerobic endurance. From August to October/November, the focus is on on-snow training, interspersed with short periods of recovery and physical conditioning designed to maintain general condition and develop sport-specific qualities such as power.

The costs of traveling overseas for ski training and for preparing ski arenas (snow surface, netting/safety, etc.) require such training to be concentrated into blocks of 1–4 weeks. Teams with access to nearby glaciers have reduced travel and infrastructure costs and can choose to conduct more, but shorter (4–5 days) blocks of ski training on these glaciers. The choice between training on nearby glaciers or overseas depends not only on the cost, duration and frequency of on-snow training blocks, but also on altitude and snow conditions. To minimize accumulated fatigue and maximize training quality, the use of a larger number of shorter training blocks at moderate or low altitude is advantageous. Since the interaction between skis and snow on a glacier differs from that on natural and man-made snow and all World Cup races (except for the opening race in October) are held on the latter, it is important that equipment be tested under World Cup-like snow conditions before the season starts. This is one of the reasons why teams travel to the southern hemisphere. However, long trips, especially those over several time zones, influence the load of training and require extra recovery.

During August and September teams generally travel to train on nearby glaciers or on winter/spring snow in the southern hemisphere. During this period the athletes live at low or moderate altitude and ski at moderate or high altitude (with the exception of Chile, where skiers both live and train at high altitude).

During October, temperatures at high altitude provide good training conditions and teams prepare on glaciers in the Alps for the opening World Cup race in October. During November, or as soon as climate and snow conditions permit, training moves to ski areas with man-made snow and more variable terrain. During this period it is critical to finalize the choice and preparation of equipment, particularly for aggressive artificial snow, before the tight competition schedule begins.

## THE COMPETITION PERIOD

Physical training during the competition period is designed to (1) maintain physical fitness; (2) achieve peak physical form for competitions; (3) engage in active recovery and rehabilitation of injuries; and (4) provide relaxation/fun (distraction from competition), and is governed by the racing schedule and on-snow training. Specifically, between races skiers prepare for technical aspects of the upcoming races (such as terrain, course setting, snow and light conditions, and adaptation of equipment), while physical fitness *per se* is not optimized to the same extent as in the case of some other sports with less varied forms of exercise, e.g., certain endurance sports.

During a typical week of competition, skiers participate in 1–3 races and perform 1–4 sessions of ski training. Physical training is adapted to travel load, recovery, and health. Technical competitions are usually conducted on the weekend, leaving weekdays for training and travel, often to a training base somewhere in central Europe. Athletes competing in DH complement their races with the official training runs permitted on the course used for competition, which greatly limits their total weekly volume of training.

A day with competition starts with a physical warm-up, followed by a skiing warm-up, inspection of the course and a second physical warm-up. For events involving several runs the physical warm-up is repeated prior to each run. During weeks without competition, training is similar to the light ski training during the preparation period (see **Table 2**).

When scheduling competitions, the International Ski Federation attempts to minimize the requirement for travel, especially between time zones, which is a potential risk for illness and injury (Spörri et al., 2012, 2016). Nonetheless, competition periods from November to March are continuously intense. Skiers seldom skip races in order to recover or train specifically for major events, since competition appears to be the best way to train for the snow conditions and course preparation involved in major events. Preparation of downhill courses in particular requires much time and effort, so few ski resorts allow these to be used for training during the tourist season. Accordingly, downhill races and official training associated with races offer the best training possibilities. Athletes also avoid skipping races in order to keep their starting position and enhance the potential to win prize money.

# FUTURE PERSPECTIVES

Competition in elite sports drives continuous development of human athletic performance, always pushing limits. In the section below, we explore potential approaches to improving the training of alpine ski racers.

## Ski Training Volume

As already discussed, the total volume of competition-specific training of technique is limited by a number of physiological, psychological, and practical factors. Innovative approaches to increasing the volume of training, while optimizing recovery and health, may further improve performance. For instance, the capacity for ski training on any single day may be enhanced by elevating physical capacity through better conditioning. Further increases in ski training volume may be made possible by selecting training venues at lower altitudes, reducing the fatigue associated with exposure to high altitude. Improvements in snow-making technology and snow storage may help to counter the threat of climate change to snow packs around the globe (Pachauri and Meyer, 2014), which is steadily reducing possibilities for on-snow ski training (Wolfsperger et al., 2018). In addition, short-term weather exerts a major impact on ski training and an improved ability to adapt to unexpected changes in weather and snow conditions – for example, by limiting the size of training groups – can allow greater volume, as well as better quality. In addition, close collaboration with ski area operators may enable teams to increase training volume by prolonged access to lifts and training slopes or the use of transportation, such as snowmobiles, that reduce the turn-around time between runs. Certain modifications in the annual schedule may also allow more on-snow training, e.g., scheduling such training when it can be performed at local ski areas at low altitude. Skiing indoor is also becoming more popular, particularly during summer, when snow conditions on glaciers are deteriorate due to elevated temperatures. For many nations, on-snow training during April and May is relatively inexpensive, snow conditions are often good for long periods of the day, and training at lower altitudes is thus possible. This training is designed to maintain the athlete's skiing skills throughout the training season and test new equipment (skis/boots) for the upcoming competition period.

## The Effectiveness of Ski Training

Regardless of how well-trained an athlete is, the volume of on-snow training will always be limited by fatigue and health issues. However, the potential to improve the effectiveness of this training in terms of learning and transferring skills to competition is essentially unlimited. For example the use and combination of holistic full course versus element training. Insights into the basic concepts of motor learning – such as the distribution, variability, and specificity of practice; the use of verbal instructions and feedback (always); appropriate employment of augmented feedback from video (following every training session), timing (always, except during the early preparation phase) and other sensors; and mental practice (Magill and Anderson, 2017) – can potentially improve ski technique training considerably. Moreover, optimizing the organization and form of ski training might enhance effectiveness. Most ski training is conducted holistically, including more or less all of the different aspects of skiing competition. To increase the number of repetitions of a certain element and improve focused learning, more element training might be beneficial. Additional focus on individual elements or certain conditions might be beneficial. For instance, climate change may lead to softer, more difficult snow conditions during competition, as well as to bumpier courses for top athletes who start late in the second run of technical events. Accordingly, **t**raining under sub-optimal snow conditions may become more important in the future.

## Physical Conditioning

The physical training of alpine skiers is complex, focusing on multiple capacities such as strength and endurance during the same period. In periods when off- and on-snow training are combined, technical training should not be compromised by fatigue due to physical training. Clearly, a better understanding of the effects of training on the various components of fitness, in combination with technical training, could guide coaches in their attempts to improve the quality and volume of physical training. More research on physical conditioning and its combination with on-snow training is definitely needed.

## Health, Training, and Performance

Most Olympic athletes have a history of injury and suffer from some sort of chronic injury that affects training. Thus, for many athlete's, his/her health governs the training schedule to large extent. Balancing training loads with appropriate recovery is therefore essential for effective training, but not always easy for coaches and health care personnel to achieve in practice. The Olympic athlete might be among the athletes who have developed a good feeling for the balance between load and recovery, since this skill might be one of the reasons why they became Olympic athletes. New technology, such as wearable sensors, might facilitate finding this balance by improving quantification of the loads imposed by on-snow training and competition (Gilgien et al., 2013, 2018; Fasel et al., 2016).

# AUTHOR CONTRIBUTIONS

MG, RR, CR, MS, and H-CH designed the study. MG, RR, and H-CH collected the data. MG analyzed the data. All authors contributed to the writing the manuscript.

# ACKNOWLEDGMENTS

We would like to thank all of the coaches and scientists who shared their experience and knowledge with us for this study.

## REFERENCES

Fasel, B., Spörri, J., Gilgien, M., Boffi, G., Chardonnens, J., Müller, E., et al. (2016). Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors. *Remote Sens.* 8:671. doi: 10.3390/rs8080671

Ferguson, R. A. (2010). Limitations to performance during alpine skiing. *Exp. Physiol.* 95, 404–410. doi: 10.1113/expphysiol.2009.047563

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015a). Characterization of course and terrain and their effect on skier speed in world cup alpine ski racing. *PLoS One* 10:e0118009. doi: 10.1371/journal.pone.0118119

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015b). Correction: characterization of course and terrain and their effect on skier speed in World Cup alpine ski racing. *PLoS One* 10:e0118119. doi: 10.1371/journal.pone.0128899

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gilgien, M., Spörri, J., Kröll, J., Crivelli, P., and Müller, E. (2014). Mechanics of turning and jumping and skier speed are associated with injury risk in men's World Cup alpine skiing: a comparison between the competition disciplines. *Br. J. Sports Med.* 48, 742–747. doi: 10.1136/bjsports-2013-092994

Haaland, B., Steenstrup, S. E., Bere, T., Bahr, R., and Nordsletten, L. (2015). Injury rate and injury patterns in FIS World Cup Alpine skiing (2006–2015): have the new ski regulations made an impact? *Br. J. Sports Med.* 50, 1–6. doi: 10.1136/bjsports-2015-095467

Hydren, J. R., Volek, J. S., Maresh, C. M., Comstock, B. A., and Kraemer, W. J. (2013). Review of strength and conditioning for alpine ski racing. *Strength Cond. J.* 35, 10–28. doi: 10.1519/SSC.0b013e31828238be

Maffiuletti, N. A., Impellizzeri, F., Rampinini, E., Bizzini, M., and Mognoni, P. (2006). Is aerobic power really critical for success in alpine skiing? *Int. J. Sport. Med.* 27, 166–167. doi: 10.1055/s-2006-923854

Magill, R. A., and Anderson, D. I. (2017). *Motor Learning and Control: Concepts and Applications*. New York, NY: McGraw-Hill Education.

Matveyev, L. P. (1981). *Fundamentals of Sports Training*, 1st Edn, ed. A. P. Zdornykh (Moscow: Progress Publishers).

Neumayr, G., Hoertnagl, H., Pfister, R., Koller, A., Eibl, G., and Raas, E. (2003). Physical and physiological factors associated with success in professional alpine skiing. *Int. J. Sports Med.* 24, 571–575. doi: 10.1055/s-2003-43270

Pachauri, R. K., and Meyer, L. A. (2014). *IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC. Available at: http://www.ipcc.ch/report/ar5/syr/

Patterson, C., and Raschner, C. (2015). "Eccentric overload squats with the intelligent motion lifter: strength training for alpine ski racing," in *Science and Skiing VI*, eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Maidenhead: Meyer & Meyer Sort), 260–267.

Patterson, C., Raschner, C., and Platzer, H. P. (2009). Power variables and bilateral force differences during unloaded and loaded squat jumps in high performance alpine ski racers. *J. Strength Cond. Res.* 23, 779–787. doi: 10.1519/JSC.0b013e3181a2d7b3

Patterson, C., Raschner, C., and Platzer, H. P. (2014). The 2.5-minute loaded repeated jump test: evaluating anaerobic capacity in alpine ski racers with loaded countermovement jumps. *J. Strength Cond. Res.* 28, 2611–2620. doi: 10.1519/JSC.0000000000000436

Polat, M. (2016). An examination of respiratory and metabolic demands of alpine skiing. *J. Exerc. Sci. Fit.* 14, 76–81. doi: 10.1016/j.jesf.2016.10.001

Raschner, C., Hildebrandt, C., Mohr, J., and Müller, L. (2017). Sex differences in balance among alpine ski racers: cross-sectional age comparisons. *Percept. Mot. Skills* 124, 1134–1150. doi: 10.1177/0031512517730730

Raschner, C., Müller, L., Patterson, C., Platzer, H. P., Ebenbichler, C., Luchner, R., et al. (2013). Current performance testing trends in junior and elite Austrian alpine ski, snowboard and ski cross racers. *Sport. Orthop. Traumatol.* 29, 193–202. doi: 10.1016/j.orthtr.2013.07.016

Raschner, C., Patterson, C., and Müller, E. (2004). "Coordination and stabilization oriented strength training with multifunctional training devices in a long-term training program of young Austrian ski racers," in *Proceedings of the 3rd International Congress on Skiing and Science*, eds D. Bacharach and J. Seifert (Snowmass: St. Cloud State University), 93–94.

Reid, R. (2000). *The Planning of Training for Highly Qualified Alpine Ski Racers: The Philosophies of Expert Coaches*. Available at: https://www.skiforbundet.no/contentassets/93727ceee6f845ed87a63124d4cb9ada/fagstoffalpint_planningoftraining_robertreid.pdf

Reid, R. (2010). *A Kinematic and Kinetic Study of Alpine Skiing Technique in Slalom*. Available at: https://brage.bibsys.no/xmlui/bitstream/handle/11250/171325/reid phd 2010.pdf?sequence=1&isAllowed=y

Spörri, J., Kröll, J., Amesberger, G., Blake, O., and Müller, E. (2012). Perceived key injury risk factors in World Cup alpine ski racing an explorative qualitative study with expert stakeholders. *Br. J. Sports Med.* 46, 1059–1064. doi: 10.1136/bjsports-2012-091048

Spörri, J., Kröll, J., Gilgien, M., and Müller, E. (2016). How to prevent injuries in alpine ski racing: what do we know and where do we go from here? *Sports Med.* 47, 599–614. doi: 10.1007/s40279-016-0601-2

Supej, M., and Holmberg, H. C. (2010). How gate setup and turn radii influence energy dissipation in slalom ski racing. *J. Appl. Biomech.* 26, 454–464. doi: 10.1123/jab.26.4.454

Turnbull, J. R., Kilding, A. E., and Keogh, J. W. L. (2009). Physiology of alpine skiing. *Scand. J. Med. Sci. Sports* 19, 146–155. doi: 10.1111/j.1600-0838.2009.00901.x

Wolfsperger, F., Rhyner, H., and Schneebeli, M. (2018). *Pistenpräparation und Pistenpflege. Das Handbuch für den Praktiker*. Davos: WSL-Institut für Schnee- und Lawineforschung SLF. Available at: https://www.dora.lib4ri.ch/wsl/islandora/object/wsl:17135

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ORIGINAL RESEARCH
published: 25 July 2018
doi: 10.3389/fphys.2018.00962

# Hypoxia and Fatigue Impair Rapid Torque Development of Knee Extensors in Elite Alpine Skiers

Marine Alhammoud[1,2], Baptiste Morel[3], Olivier Girard[4,5], Sebastien Racinais[5,6]*, Violaine Sevrez[7], Alexandre Germain[8], Thomas Chamu[8] and Christophe Hautier[1]*

[1] Inter-university Laboratory of Human Movement Biology (EA 7424), Claude Bernard University Lyon 1, Lyon, France, [2] French Ski Federation, Annecy, France, [3] Laboratory "Movement, Interactions, Performance" (EA 4334), Le Mans University, Le Mans, France, [4] School of Psychology and Exercise Science, Murdoch University, Perth, WA, Australia, [5] Athlete Health and Performance Research Centre, Aspetar Orthopedic and Sports Medicine Hospital, Doha, Qatar, [6] Laboratory Sport, Expertise and Performance, French Institute of Sport (INSEP), Paris, France, [7] French National Center for Scientific Research, Institute of Movement Sciences, Aix-Marseille University, Marseille, France, [8] Orthopedic and Sports Medicine Hospital La Sauvegarde, Lyon, France

OPEN ACCESS

**Edited by:**
Gianluca Vernillo,
Università degli Studi di Milano, Italy

**Reviewed by:**
Tadej Debevec,
University of Ljubljana, Slovenia
Martin Burtscher,
Universität Innsbruck, Austria
Stuart Goodall,
Northumbria University,
United Kingdom

***Correspondence:**
Sebastien Racinais
sebastien.racinais@aspetar.com
Christophe Hautier
christophe.hautier@univ-lyon1.fr

**Specialty section:**
This article was submitted to
Exercise Physiology,
a section of the journal
Frontiers in Physiology

**Received:** 25 May 2018
**Accepted:** 29 June 2018
**Published:** 25 July 2018

**Citation:**
Alhammoud M, Morel B, Girard O, Racinais S, Sevrez V, Germain A, Chamu T and Hautier C (2018) Hypoxia and Fatigue Impair Rapid Torque Development of Knee Extensors in Elite Alpine Skiers. Front. Physiol. 9:962. doi: 10.3389/fphys.2018.00962

This study examined the effects of acute hypoxia on maximal and explosive torque and fatigability in knee extensors of skiers. Twenty-two elite male alpine skiers performed 35 maximal, repeated isokinetic knee extensions at 180°s$^{-1}$ (total exercise duration 61.25 s) in normoxia (NOR, $FiO_2$ 0.21) and normobaric hypoxia (HYP, $FiO_2$ 0.13) in a randomized, single-blind design. Peak torque and rate of torque development (RTD) from 0 to 100 ms and associated *Vastus Lateralis* peak EMG activity and rate of EMG rise (RER) were determined for each contraction. Relative changes in deoxyhemoglobin concentration of the VL muscle were monitored by near-infrared spectroscopy. Peak torque and peak EMG activity did not differ between conditions and decreased similarly with fatigue ($p < 0.001$), with peak torque decreasing continuously but EMG activity decreasing significantly after 30 contractions only. Compared to NOR, RTD, and RER values were lower in HYP during the first 12 and 9 contractions, respectively (both $p < 0.05$). Deoxyhemoglobin concentration during the last five contractions was higher in HYP than NOR ($p = 0.050$) but the delta between maximal and minimal deoxyhemoglobin for each contraction was similar in HYP and NOR suggesting a similar muscle $O_2$ utilization. Post-exercise heart rate (138 ± 24 bpm) and blood lactate concentration (5.8 ± 3.1 mmol.l$^{-1}$) did not differ between conditions. Arterial oxygen saturation was significantly lower (84 ± 4 vs. 98 ± 1%, $p < 0.001$) and ratings of perceived exertion higher (6 ± 1 vs. 5 ± 1, $p < 0.001$) in HYP than NOR. In summary, hypoxia limits RTD via a decrease in neural drive in elite alpine skiers undertaking maximal repeated isokinetic knee extensions, but the effect of hypoxic exposure is negated as fatigue develops. Isokinetic testing protocols for elite alpine skiers should incorporate RTD and RER measurements as they display a higher sensitivity than peak torque and EMG activity.

**Keywords: isokinetic, maximal torque production, near-infrared spectroscopy, neural drive, repeated knee extensions, simulated altitude**

## INTRODUCTION

Alpine skiing requires a high activation level of the knee extensor muscles to sustain repeated, near maximal contractions (Ferguson, 2010) for 45–120 s (Berg and Eiken, 1999). Exercise-induced muscle fatigue can be defined as a reduction in the maximum force that a muscle can exert and/or sustain (Enoka, 2002). Reportedly, skiing-induced fatigue is manifested by decreases in hamstring and quadriceps eccentric torque for 1–24 h following a 4-h skiing session (Koller et al., 2015). Hence, skiing-induced fatigue alters force production capacity and electromyographic (EMG) activity in the lower extremities (Kröll et al., 2005, 2011; Ushiyama et al., 2005; Akutsu et al., 2008; Tomazin et al., 2008; Kiryu et al., 2011). Neuromuscular consequences of fatigue development for the *vastus lateralis* (VL) muscle also include a decline in mean power frequency in the first half of a 1–2 min ski run (Ushiyama et al., 2005) and the presence of high-frequency fatigue after ∼45 s of slalom (Tomazin et al., 2008).

Recent studies have suggested that the rate of torque development (RTD) within the initial phase of a contraction represents a more functional outcome measure than maximal torque *per se* (Girard and Millet, 2009; Jordan et al., 2015). A decreased in RTD was also associated with poor jumping/hopping performance and abnormal knee loading, potentially increasing injury risk (Pua et al., 2017). RTD is important to stabilize the musculo-skeletal system in response to mechanical perturbation (Folland et al., 2014). This may especially be true in skiing where the time available to develop force is short. Arguably, a high RTD may help preventing falls and injury in alpine skiing, where anterior cruciate ligament (ACL) injury typically occurs in a time-window of 200 ms (Bere et al., 2011). Indeed, alpine skiing requires immediate postural adjustments to prevent falls in response to a loss of balance onto uneven ski slopes at high speed. Importantly, a greater injury risk was reported in World Cup skiers in the final section of the course pointing out fatigue as a possible contributing factor (Bere et al., 2014). Thus, studying the effect of fatigue on RTD may help to shed more light on the underpinning neuromuscular factors responsible for the high injury rate in elite skiers (Jordan et al., 2015, 2017; Haaland et al., 2016).

The repetition of near maximal contractions while skiing also generate high intramuscular pressures, likely reducing muscle perfusion and thereby oxygen delivery/waste removal (Szmedra et al., 2001). This effect may be more prominent in Giant Slalom (GS) than Slalom (SL) due to a more flex position with higher forces (Turnbull et al., 2009), and even more pronounced in Super Giant Slalom where the average knee angular velocity is low (Berg and Eiken, 1999). Using near-infrared spectroscopy (NIRS) a 33% greater oxygen desaturation of the VL along with a 30% greater blood volume change have been reported during GS than SL (Szmedra et al., 2001). In competitive speed-skating, increased deoxygenation in the capillary bed of the exercising quadriceps was demonstrated during characteristic low sitting versus upright position (Rundell et al., 1997). Given that the rhythmic pattern of GS or SL only allows a partial reperfusion of working muscles in alpine skiers (Szmedra et al., 2001), a comprehensive investigation of the time course and etiology of fatigue development in skiers should also include quadriceps muscle deoxygenation trends.

Lastly, the vascular occlusions during the forceful contractions of ski racing (Tesch et al., 1978) increase lactate production, as does the hypoxic environment when competing at altitude (Turnbull et al., 2009). Indeed, alpine skiing is performed at moderate-to-high terrestrial altitude, with sometimes starting gate as high as ∼3,500 m above sea level (Beaver Creek, CO, United States), creating a unique challenge on skiers. Hypoxia has been demonstrated to impair exercise capacity during repeated, maximal leg extensions (Goodall et al., 2010; Christian et al., 2014) partly through an alteration in neural drive (Amann and Calbet, 2008; Goodall et al., 2010; Billaut et al., 2013). Such alterations, when altitude severity is >2000 m, can increase risk of fall and injury occurrence in recreational skiers (Burtscher et al., 2009). The acute effects of hypoxia on performance involving repeated bouts of short high intensity efforts without long recovery time are not negligible and deserve more research attention in elite skiers (Chapman et al., 2010).

The aim of this study was to assess the time course and magnitude of changes in peak and rapid torque production together with neuromuscular and metabolic adjustments in the VL during repeated maximal leg extensions in elite alpine skiers. We hypothesized that, compared to normoxia, hypoxia exposure would exacerbate muscle deoxygenation causing further reductions in maximal torque and rapid torque development through a lower central motor drive.

## MATERIALS AND METHODS

### Participants

Twenty-two elite male alpine skiers (mean ± SD stature 179 ± 4 cm, body mass 83 ± 6 kg, age 26 ± 4 years) participated in this study. All were members of the French national team (including world champions and Olympic medalists) with a background training of >200 days per year for several years. The project was approved by the Aspetar scientific committee (approval number CMO/000058/fj) and the ADL-Q ethics committee (approval number E20140000011). All subjects gave written informed consent in accordance with the Declaration of Helsinki.

### Experimental Design

Participants performed a fatiguing exercise (see below) in normoxic [NOR, sea level, inspired $O_2$ fraction ($FiO_2$) 0.21] and normobaric hypoxic (HYP, simulated altitude of 3,800 m, $FiO_2$ 0.13) conditions, in a random order and using a single-blind design. The two exercise tests took place on the same day and were separated by 2 h, during which the participants resting quietly on a chair with no specific recovery intervention. This was based on the observation that 10–30-min rest periods allow an almost complete recovery of neuromuscular function

**Abbreviations:** EMGpeak, peak EMG; HYP, normobaric hypoxia; NOR, normoxia; RER, rate of EMG rise; Tpeak, peak torque.

parameters after high-intensity single-joint quadriceps exercise (Gruet et al., 2014) or repeated sprint running exercise (Perrey et al., 2010). Additionally, the elite athletes recruited here were used to train twice a day and were accustomed to heavy resistance training. This procedure also permitted to keep the EMG sensors at the exact same location to avoid methodological difficulty in comparing EMG data on separate days. All participants were tested between 9:00 and 19:00 in a temperate room, with no other training done on that day. Participants were instructed to avoid strenuous activities for 48 h before testing and to follow their normal diet and sleeping habits. Prior to the fatiguing exercise, participants completed a standardized warm-up including 10 min of cycling at 1 $W \cdot kg^{-1}$ followed by knee extensions (8 × $240°s^{-1}$; 6 × $180°s^{-1}$; 4 × $90°s^{-1}$; 2 × $30°s^{-1}$; 2 × $0°s^{-1}$; with 45 s recovery between sets) at progressively increased subjective awareness of effort (70–100% of maximal perceived intensity). Thereafter, participants rested in a seated position for 5 min before exercise commencement. For both trials, a facemask connected to a portable hypoxic generator (Altitrainer, SMTEC, Nyon, Switzerland), controlling the $FiO_2$ at the required level during the warm-up knee extensions and the fatiguing exercise, was attached on subjects. All participants were used to the system as they regularly use it during their training. However, they were not specifically acclimated to hypoxia when experiments were conducted as testing occurred during the early pre-season (June), approximately 1 month before engaging in a complete block of altitude training (July–August).

## Exercise

The fatigue protocol was performed on an isokinetic dynamometer (Contrex, CMV AG, Dübendorf, Switzerland). Calculation of the limb weight was carried out during passive movements and gravity correction was performed with the ConTrex-MJ software (Contrex, CMV AG, Dübendorf, Switzerland). The subjects were seated with their hip joint angles set at 80° (0° is full extension) and their chest and working leg tightly fixed against the chair. They were asked to cross their arms over the chest during the contractions. The protocol consisted of 35 maximal, repeated isokinetic knee extensions of the dominant leg at $180° \cdot s^{-1}$, from 90° to 45° of knee flexion (0° is full knee extension). Each contraction lasted 250 ms and the total exercise duration was 61.25 s. At the end of each maximal knee extension, the participants were instructed to relax their leg while the isokinetic device returned to its initial position at $30°s^{-1}$ (i.e., 1.5 s). Participants were instructed to "push as fast and as hard as possible." While the protocol involves the completion of 35 knee extensions only the first 34 were further analyzed to avoid the bias of the apparatus stop. Participants were provided with a real-time feedback allowing them to visualize the torque produced during each maximal knee extension. Strong verbal encouragement was provided throughout.

## Torque Measurements

Torque and angular velocity were recorded (sampling rate: 256 Hz) to calculate peak torque ($T_{peak}$) and RTD. RTD was calculated as the slope of the torque vs. time curve between 0 and 100 ms relative to the contraction onset. We have decided to focus our analysis on the initial 100 ms after contraction onset for the following reasons: (1) RTD seems to be mainly determined by the capacity to produce maximal voluntary activation in the early phase of an explosive contraction (within 100 ms) particularly as a result of increased motor unit discharge rate; (2) there is a greater variability during the early phase of the contraction (especially the first 50 ms); (3) despite rapid muscle activation being a critical determinant of RTD, the voluntary RTD becomes increasingly influenced by muscle properties and maximal force for duration longer than 100 ms (Maffiuletti et al., 2016).

## Electromyography

EMG activity of the VL was recorded using surface electrodes (EMG Triode, nickel-plated brass, electrode diameter = 1 cm, inter-electrode distance = 2 cm, Thought Technology, Montreal, QC, Canada). The same electrodes were kept in place for both tests sessions to ensure that EMG activity signals representative of the same muscle area could be compared by using repeated measures. Albeit surface EMG recordings can be affected by extreme environmental temperatures (Bell, 1993; Racinais, 2013), the current protocol was performed under temperate ambient conditions. EMG signals were sampled at 2048 Hz using the Flexcomp Infiniti system (Thought Technology, Montreal, Canada). The system had an input impedance and common mode rejection ratio of 2 MΩ and $>110$ dB, respectively. The skin was shaved and cleaned with alcohol before placing electrodes to improve the contact between skin and electrode and to reduce skin impedance. Raw EMGs were filtered (Butterworth order 2, bandpass 10-500 Hz) and amplified (gain = 500) before calculating root mean squared values (RMS) with a 50-ms moving rectangular window (MATLAB scripts, Mathworks, Natick, MA). The onset of the RMS bursts was detected using the threshold method described by Morel et al. (2015) based on ± 3 SD of the resting baseline. For each contraction, the following EMG variables were extracted: Peak EMG ($EMG_{peak}$) calculated over a 50 ms period and RER defined as the slope of the EMG–time curve between 0 and 100 ms relative to the activation onset.

## Muscle Oxygenation Trends

Relative changes in deoxyhemoglobin concentration [HHb] of the VL muscle were monitored (sampling frequency 20 Hz) by NIRS (Portamon, Artinis, Zetten, Netherlands). Whereas various parameters can be extracted by NIRS, we selected [HHb] as it is insensitive to blood volume during exercise (De Blasi et al., 1993; Ferrari et al., 1997), and thus represents a reliable indicator of changes in oxygen extraction when investigating exercise-induced fatigue (De Blasi et al., 1994; Ferrari et al., 1997). The optodes were fixed at 40 mm distance between the light source and the detector. The optode assembly was secured on the cleaned skin surface with tape and then covered with a black cotton tissue. The light emitted by the infrared probe is assumed to reach a tissue depth of 50% of the interoptode spacing (Matsushita et al., 1998). Skinfold thickness was measured using a skinfold caliper. The obtained value was 6.5 ± 2.9 mm, which was well below the penetration depth of the NIRS photons. A differential pathlength factor of 3.8 was used for the VL muscle

(DeLorey et al., 2005). Changes in [HHb] were reported as an absolute change from baseline that was measured during 1 min at rest before the exercise and were used as an estimator of changes in intramuscular oxygenation. Total hemoglobin (tHb) was also calculated. Changes in [HHb] and tHb during the exercise were analyzed during the last 5 contractions (i.e., at steady state) as the mean difference between maximal and minimal values (Δ min-max [HHb], Δ min-max tHb, respectively) (**Figure 1**).

## Systemic Responses

### Heart Rate

Heart rate (HR) was continuously monitored at 5-s intervals during all trials using a heart rate monitor connected to a chest strap (RS800, Polar Electro OY, Kempele, Finland) and the resting and post-exercise (i.e., 15 s after exercise cessation) values were extracted.

### Ratings of Perceived Exertion

After each session, participants were asked to indicate their ratings of perceived exertion (RPE) using a Borg CR-10 scale (Borg, 1990).

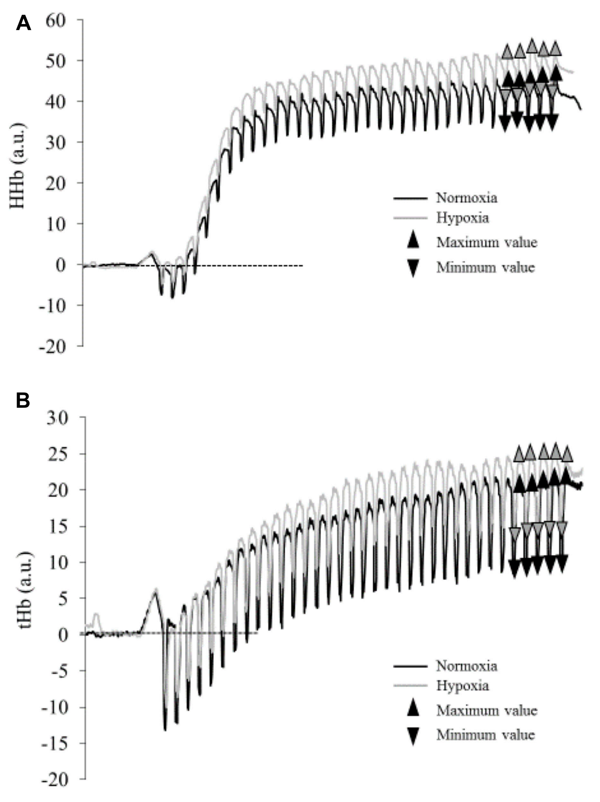


**FIGURE 1 |** Typical traces of deoxyhemoglobin concentration [HHb] **(A)** and total hemoglobin (tHb) **(B)** during the fatiguing protocol in normoxia (black line) and hypoxia (gray line) for one subject. Triangles represent maximal and minimal values measured during the last five contractions (mean values are presented in **Table 1**).

### Arterial Saturation

Percent arterial oxygen saturation ($SpO_2$, %) was measured before and at the end of the exercise using a fingertip pulse oximeter (Onyx II, Model 9560, Nonin, Plymouth, MN, United States).

### Blood Lactate

A micro blood sample was taken from the fingertip before and 3 min after the end of the exercise. The sample was analyzed for lactate concentration using a Lactate Pro (LT-1710, Arkray, Japan) portable analyzer.

## Statistical Analysis

Data were analyzed with Statistica 8.0 Software (Stat Soft Inc.®, Tulsa, OK, United States). The normality of the error distribution was examined with Lilliefors' test. Homogeneity of variance was verified using Levene's test. With the assumption of normality and homogeneity of variance confirmed, data were analyzed using two-ways repeated-measures ANOVAs (time x condition). Tukey's *post hoc* tests were used. Finally, a paired Student's *t*-test was performed to compare the blood lactate accumulation, $SpO_2$, end exercise heart rate, and rate of perceived exertion during NOR and HYP. Effect-sizes are described in terms of partial eta-squared ($\eta^2$, with $\eta^2 \geq 0.06$ representing a moderate effect and $\eta^2 \geq 0.14$ a large effect). Alpha level for statistical significance was set at $p \leq 0.05$. Data are presented as means ± Standard Deviation (SD). 95% confidence interval (CI95%) are reported for [HHb] and tHb data.

# RESULTS

## Torque

$T_{peak}$ decreased steadily during the exercise (**Figure 2A**, $p < 0.001$; $\eta^2 = 0.84$), without a significant difference between conditions ($p = 0.992$) or any interaction effect ($p = 0.725$). Conversely, there was an interaction effect on RTD (**Figure 2B**, $p = 0.002$; $\eta^2 = 0.50$) with significantly lower values in HYP vs. NOR during the first 12 contractions only. Compared to the first contraction, RTD values decreased significantly from the nineteenth contraction in NOR and from the twenty-eighth contraction in HYP.

## EMG

$EMG_{peak}$ significantly decreased with fatigue ($p < 0.001$; $\eta^2 = 0.24$) and was lower during the last four contractions as compared to the first contraction (**Figure 3A**), yet without a significant difference between conditions ($p = 0.951$) or any interaction effect ($p = 0.324$). Conversely, there was an interaction effect on RER (**Figure 3B**, $p < 0.001$; $\eta^2 = 0.43$) with significantly lower values in HYP vs. NOR during the first 9 contractions only. RER significantly decreased with fatigue in NOR, whereas it remained unchanged in HYP (**Figure 3B**).

## Muscle Deoxygenation

The maximal [HHb] ($p = 0.050$; $\eta^2 = 0.25$) but not tHb ($p = 0.186$; $\eta^2 = 0.12$) measured during the last 5 contractions

**TABLE 1 |** Deoxyhemoglobin [HHb] and total hemoglobin (tHb) averaged over the last five contractions in normoxia and hypoxia.

| | [HHb] | | tHb | |
|---|---|---|---|---|
| | ***Normoxia*** | ***Hypoxia*** | ***Normoxia*** | ***Hypoxia*** |
| Peak value (a.u.) | 38.9 ± 15.7 | 41.0 ± 12.8* | 17.5 ± 8.6 | 15.8 ± 8.1 |
| CI95% peak | *32.3–45.4* | *35.6–46.3* | *13.9–21.1* | *12.4–19.2* |
| Δmin-max (a.u.) | 10.1 ± 9.8 | 11.0 ± 5.5 | 14.6 ± 8.7 | 13.9 ± 7.2 |
| CI95% Δmin-max | *6.0–14.2* | *8.7–13.2* | *10.9–18.2* | *10.9–16.9* |

*$p \le 0.05$.

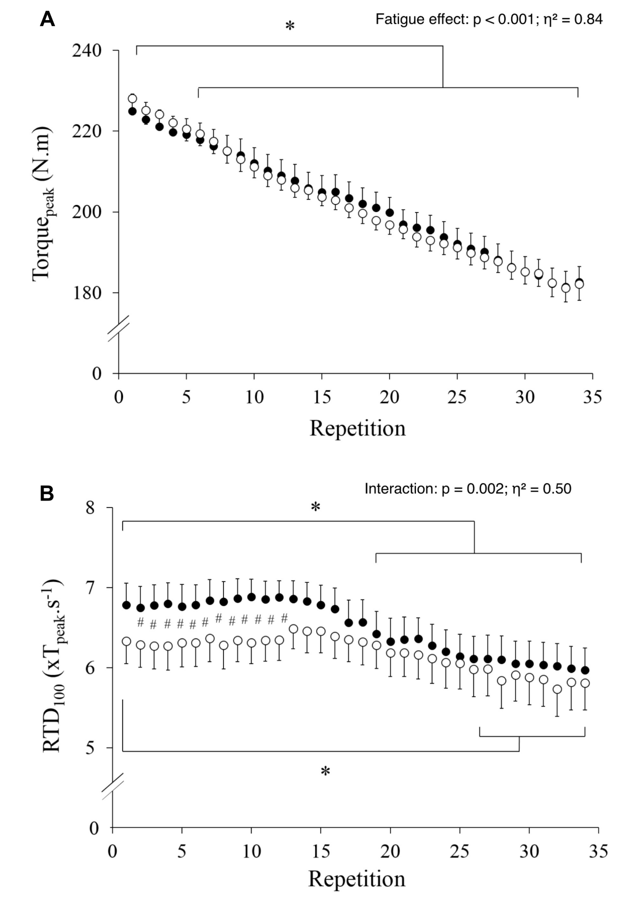


**FIGURE 2 |** Maximal torque **(A)** and rate of torque development **(B)** values measured during the 34 maximal contractions performed in normoxia (black dots) and hypoxia (open circle). Data are means ± SD for 22 participants. #$p < 0.05$ hypoxia versus normoxia; *$p < 0.001$ effect of fatigue.

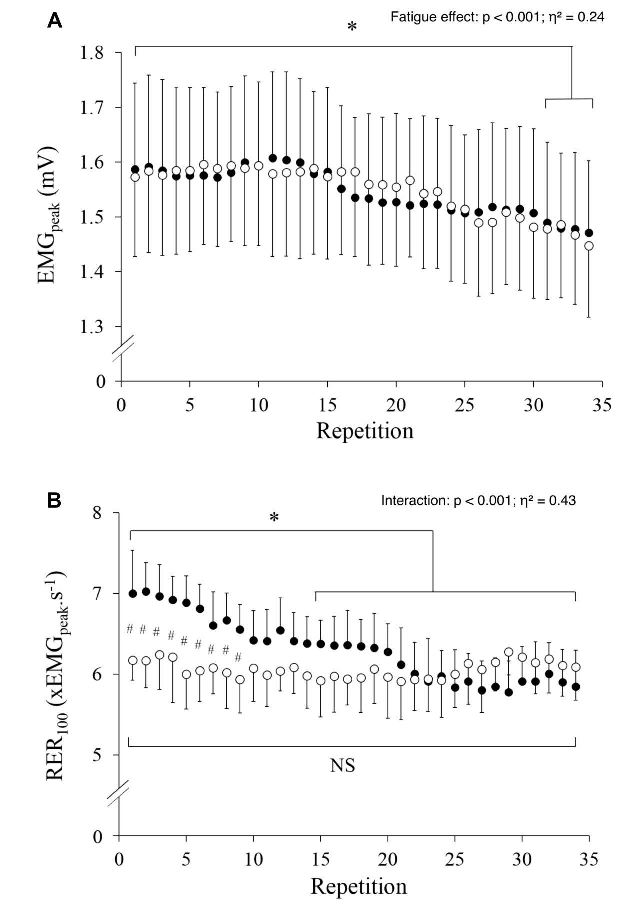


**FIGURE 3 |** Peak EMG **(A)** and rate of EMG rise **(B)** measured during the 34 maximal contractions performed in normoxia (black dots) and hypoxia (open circle). Data are means ± SD for 22 participants. #$p < 0.05$ hypoxia versus normoxia; *$p < 0.001$ effect of fatigue.

was higher in HYP compared to NOR (**Table 1** and **Figure 1**). However, the delta between maximal and minimal [HHb] and tHb throughout the last five contractions (**Table 1**) did not differ between conditions (Δ[HHb] $p = 0.956$, ΔtHb $p = 0.252$).

## Systemic Responses

HR (77 ± 16 vs. 138 ± 24 bpm; $p < 0.001$; $\eta^2 = 0.90$) and lactate (2.5 ± 1.4 vs. 5.8 ± 3.1 mmol.l$^{-1}$; $p < 0.001$; $\eta^2 = 0.72$) increased from pre to post-exercise (both $p < 0.001$), independently of condition (HR $p = 0.890$, lactate $p = 0.630$). A significant interaction between time and condition was revealed for $SpO_2$ ($p < 0.001$; $\eta^2 = 0.81$); $SpO_2$ values decreased from pre to post-exercise in HYP (92 ± 2% vs. 84 ± 4%; $p < 0.001$), whereas it did not change in NOR (98 ± 2% vs. 98 ± 1%; $p = 0.99$). RPE values were higher in HYP (5.9 ± 2.8) vs. NOR (5.1 ± 1.1) ($p < 0.001$; $\eta^2 = 0.56$).

## DISCUSSION

The objective of the present study was to determine the effects of acute hypoxic exposure on alterations in maximal and rapid torque production and accompanying neuromuscular and metabolic adjustments during maximal, repeated isokinetic knee extensions in elite alpine skiers. Our main findings were that hypoxia caused reductions in RTD and RER, whereas $T_{peak}$ and $EMG_{peak}$ remained unchanged. Importantly, the subsequent exercise-induced decreases in RTD and RER were of smaller magnitude when exercising under hypoxia, leading to similar end-exercise values with also matched muscle de-oxygenation levels between conditions.

### $T_{peak}$ and $EMG_{peak}$

In line with previous studies (Kawahara et al., 2008; Goodall et al., 2012; Christian et al., 2014), hypoxia exposure *per se* had no effect on maximal torque during a single contraction (**Figure 2A**). However, the effect of hypoxia on fatigue when contractions are repeated is more contentious in the literature with some studies reporting larger decline in torque in HYP than NOR (Goodall et al., 2010; Christian et al., 2014), whereas other concluded to no differences (Kawahara et al., 2008). Our current results confirmed the later, with a similar decrement in $T_{peak}$ induced by fatigue in HYP and NOR. However, with only one single severity of altitude simulation tested, it remains to be verified if graded hypoxia (with lower or more severe hypoxic conditions) actually modifies the extent of maximal force and EMG responses to our exhaustive exercise. Interestingly, the magnitude and nature (contribution of neural vs. peripheral factors) of fatigue-induced adjustments in neuromuscular function after unilateral knee extensions is dependent of hypoxia severity (Goodall et al., 2010). This implies that interpretation of our results remains specific to $FiO_2$ 0.13 (3,800 m), acknowledging that there is currently no alpine ski race starting at a higher altitude. The current results may also be specific to the population tested who is possibly less vulnerable to fatigue. Indeed, the skiers participating in this study routinely trained at altitude and elite athletes are likely to have a higher capillary density and capillary-to-fiber ratio than untrained participants (Zoladz et al., 2005); fatigue and recovery has been correlated with capillary density (Tesch and Wright, 1983) in the VL after 50 repeated consecutive maximal voluntary contractions at $180°s^{-1}$ but not with fiber type distribution.

As for $T_{peak}$, our data show an effect of fatigue on $EMG_{peak}$ but no effect of hypoxia (**Figure 3A**). This indicates that hypoxia didn't exaggerate fatigue-induced decrease in maximal neural drive to the VL of elite skiers. This partly differs from a previous report suggesting that a diminished $O_2$ availability in the brain could cause a failure of drive from the motor cortex during whole-body exercise (Goodall et al., 2012), with the downregulation in quadriceps muscle recruitment under hypoxia limiting muscle fatigue (Billaut et al., 2013). However, this is in line with the observation that hypoxia does not modify central regulation of motor drive during localized exercise involving a small muscle mass (Rupp et al., 2015). $EMG_{peak}$ was maintained for the first 15 contractions in the current study despite an overall decrease in $T_{peak}$ and a lower $SpO_2$ in HYP, suggesting that the decrease in $T_{peak}$ was mainly due to peripheral fatigue with no or limited recruitment downregulation during maximal contractions. This also complete previous reports showing that elite skiers better tolerate fatigue (Akutsu et al., 2008) or environmental conditions such as cold (Racinais et al., 2017) than the general population.

### RTD and RER

There has been a shift toward power training and heavier skiers over the past years in alpine ski racing (Turnbull et al., 2009) and top-level power athletes are characterized by a markedly greater knee extensor RTD measured during the initial 150 ms than habitually active individuals (Tillin et al., 2010). However, our results showed that RTD is reduced by hypoxia, i.e., a common environmental stressor for alpine skiers. The unique finding that hypoxia impairs RTD with a preserved $T_{peak}$ might at first appear in contradiction with the further reduction in $T_{peak}$, but not RTD, that was previously reported following repeated sprints in hypoxia (Girard et al., 2016). However, in that previous study, the neuromuscular test battery was performed in normoxia before and after the fatiguing task. When only considering end of exercise values, our results also failed to show any significant difference in RTD between HYP and NOR. In the current study, RTD was reduced in HYP compared to NOR during the first 12 contractions only (**Figure 2B**). According to Edman and Josephson (Edman and Josephson, 2007), RTD is influenced by passive stiffness, fiber type composition, cross-bridge kinetics and neural drive. Because the two first muscular factors were probably not modified under hypoxia at the beginning of the protocol, RTD decrease could possibly be explained by cross-bridge kinetics and neural drive. Cross-bridge kinetics is influenced by metabolites accumulation and it is unlikely that this parameter was different during the first few contractions between HYP and NOR. Thus, a lower neural drive, as demonstrated by the lower RER under hypoxia in the first contractions (**Figure 3B**), likely is the primarily cause of hypoxia-induced decrement in RTD. While it may appear counterintuitive that HYP affected RER during the first 9 contractions, it should be clarified that some physiological responses were already impacted by HYP from the beginning of the exercise (e.g., SpO2 was 92% in HYP vs. 98% in NOR). No changes in $EMG_{peak}$ were observed with such rather narrow (yet clinically relevant) difference in SpO2, which may, however, have triggered a decrement in RER by teleoanticipation of the upcoming 61 s of exercise. In support, it was previously demonstrated that "all-out" pacing strategies are adopted for exercise up to 15 s, but pacing becomes apparent when exercise is expected to last 30 s or more despite the instruction to go "all-out" (Wittekind et al., 2011). This observation adds to a previous report that whereas $T_{peak}$ alterations are related to peripheral perturbations, RTD losses were associated to both central and peripheral fatigue in non-athletes in normoxic environment (Morel et al., 2015).

It should be acknowledged that other factors (not investigated in the current protocol) are also likely to affect RTD while skiing. Indeed, skiing is generally performed in cold environments. Both cold and hypoxia exposure individually decrease constant-workload (high-intensity) knee extension time to exhaustion, with the decrements being additive when both stressors are combined (Lloyd et al., 2016). This decrease was attributed to a faster rate of peripheral fatigue development (Lloyd et al., 2016). Moreover, colder muscle temperature is also known to specifically decrease RTD (Zhou et al., 1998). Lastly, there is an ongoing debate on the potential physiological differences between hypobaric and normobaric hypoxia (Millet et al., 2012). However, this debate mainly concerns aerobic adaptations or acute mountain sickness rather than neuromuscular function adjustments (Millet et al., 2012). The only specificity of real altitude while skiing relates to a decrease in aerodynamic resistances, which remains challenging to replicate under controlled laboratory conditions.

## $SpO_2$ and NIRS Data

As expected, hypoxia lowered $SpO_2$ before and after the exercise, which occurred along with higher muscle [HHb] values (**Figures 1A,B**). It should, however, be acknowledged that muscle oxygen desaturation may be larger during skiing than during isokinetic testing due to low posture, prolonged near-maximal muscle contraction and a rhythmic pattern with insufficient time to adequately re-perfuse working muscle (Szmedra et al., 2001). This may affect blood flow and oxygen delivery to working muscle. Reportedly, changes in hemoglobin/myoglobin oxygen desaturation between rest and exercise, expressed relatively to maximal oxygen desaturation determined with cuff ischemia, are greater during GS (79.2%) than SL (65.7%) (Szmedra et al., 2001). Because our data were not normalized to maximal oxygen desaturation obtained with cuff ischemia, no comparison could be made for the relative desaturation observed in the current study with this previous literature. However, irrespectively, of the absolute levels, it is of interest to note that the delta between maximal and minimal [HHb] values calculated during the last contractions were identical in the two conditions, using repeated measures with the same methods, indicating that muscle $O_2$ utilization was similar. In addition, the blood lactate accumulation was similar in NOR and HYP, suggesting an identical anaerobic energy production. These observations differ from Calbet et al. (2003) who proposed that aerobic ATP production is reduced under hypoxia and compensated by an enhanced anaerobic energy production during a Wingate test. However, the active muscle mass was relatively small in the present study compared to cycling sprint, and $O_2$ delivery to the quadriceps muscle may thus be sufficient to maintain the aerobic energy supply even when oxygen availability is reduced. Thus, the similar $O_2$ utilization and lactate production, with lower $SpO_2$ and higher RPE in HYP, indicate similar muscle energy turnover but higher whole-body stress during single leg exercise under reduced $O_2$ availability.

## Limitations

We selected the first 100 ms as the importance of a high RTD for superior sprint/acceleration capacity, in rugby players for instance, was strongly related to the proportion of maximal force achieved in the initial phase (i.e., only for RTD 100 ms) of explosive-isometric squats (Tillin et al., 2013). However, the relative contribution of the central and peripheral factors to RTD throughout the rising phase of the force-time curve may depend on the time intervals considered for analysis. A number of different windows (0–50, 50–100, 0–150, or 100–200 ms) have been used in previous studies (Jordan et al., 2015; Maffiuletti et al., 2016) and shorter (<100 ms) or longer (>100 ms) analyses may have shown slightly different results, shorter windows being more influenced by central factors (Maffiuletti et al., 2016).

In order to mimic alpine skiing, it would be necessary to sequentially decrease the severity of hypoxic exposure during the exercise as vertical drop in official competition typically ranges from 180 m (SL) to 1100 m (Downhill) within 2 min. In addition, the exercise-to-rest ratio together with the number of contractions of the fatiguing protocol could also be extended. Indeed, the gate number is 55–75 for a SL and above 30 gates for GS. Besides, the angular velocity chosen and contraction mode (concentric) may not be representative of alpine skiing discipline, even though an angular velocity of 180°/s has often been used in fatigue isokinetic protocols in footballers (Sangnier and Tourny-Chollet, 2008). Indeed, lower angular velocity (20–70°/s) with deeper knee flexion (67–140°) and predominance of eccentric/isometric work in a closed kinetic chain has been previously seen in alpine skiing (Berg and Eiken, 1999). However, RTD is typically measured under isometric conditions despite speed-related differences in motor unit activation pattern influencing rapid muscle force production (Maffiuletti et al., 2016). Occasionally, RTD has been measured during squat or leg-press which may be more relevant for practical outcomes (Maffiuletti et al., 2016). Thus, future studies should consider measuring RTD in skiers with press or during squat exercises and testing movement patterns that mimic the ski activity pattern. We acknowledge that our protocol may not be representative of alpine skiing exercise for the above-mentioned reasons, nonetheless we choose it as it allowed assessing RTD under controlled conditions.

## Practical Applications

Recent reviews point out the critical need to develop ski-specific neuromuscular screening tests and prevention programs (Jordan et al., 2017). Our results seem to support the notion that isokinetic testing protocols for elite skiers should incorporate RTD measurements. A more specific testing should also incorporate an evaluation of fatigue and hypoxia effects to better understand the skier neuromuscular function in a practical context of performing a ski run at altitude.

Because of the tremendous strength demands of ski racing especially on the quadriceps (Abe et al., 1992), the implementation of regular hamstring and quadriceps strength assessments with special reference to RTD seems warranted in the physical evaluation of uninjured skiers. In addition, Jordan et al. (2015) observed quadriceps maximal torque and RTD deficits in the ACL-reconstructed limb of the skiers up to 25 months after the surgery, whereas skiers received medical clearance to return to full competition. These deficits led to an inflated hamstring / quadriceps ratio compared with that in uninjured controls. Considering the high ACL injury and re-injury rate in elite skiers (Pujol et al., 2007), hamstring and quadriceps strength should be assessed over a long-term period after surgery to identify chronic strength deficits in ACL-reconstructed skiers. In summary, developing higher RTD values may help preventing falls and injury in alpine skiing, where ACL injury typically occurs within the first 200 ms of muscle contraction (Bere et al., 2011). Practically, RTD can be improved both by heavy-resistance and explosive strength training through hypertrophic and neural adaptations (Aagaard et al., 2002; Maffiuletti et al., 2016), which is already included in strength and conditioning program in elite skiers.

Resistance training in hypoxia (either systemic or with blood flow restriction) is a novel and popular training method potentially causing greater muscular development and strength gains versus similar training at sea level (Heitkamp, 2015; Inness et al., 2016) and a decreased fatigue in repeated sprints (Ramos-Campo et al., 2018a). Nevertheless, a recent meta-analysis concluded that resistance training in hypoxia did not produce significant change in muscular size or maximal strength when compared to normoxic resistance training (Ramos-Campo et al., 2018b). These strength gains concern usually maximal voluntary contraction but remain unclear for RTD as hypoxia-mediated neural adaptations have not yet been discovered. Further studies are therefore needed to evaluate the effectiveness of training using repeated maximal explosive contractions under simulated altitude as well as to document the dose-response relationship. We would expect an improvement in fatigue resistance on RTD (lesser drop), which is often considered a more sensitive parameter than maximal torque.

## CONCLUSION

Whereas fatigue-induced decrements in peak torque and EMG were similar in normoxia and hypoxia, the RTD and RER were initially lower during repeated, maximal isokinetic contractions in elite alpine skiers when oxygen availability was reduced. This suggests that hypoxia limits RTD via decreased neural drive to active musculature, but this effect is negated by fatigue as muscle oxygenation trends as well as RTD and RER decrements were of smaller magnitude under hypoxia. As such, muscle function integrity may be first negatively impacted by hypoxia exposure before fatigue mediated its effect on rapid torque production during alpine ski races.

## DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

## AUTHOR CONTRIBUTIONS

MA, SR, and CH designed the study. MA, BM, SR, VS, AG, TC, and CH collected the data. MA, BM, OG, SR, and CH analyzed the data and drafted the manuscript. All authors revised and approved the manuscript.

## ACKNOWLEDGMENTS

We thank the skiers for their patience, kindness, and investment. We also thank Thibaut Trameau and Nicolas Cabaret (physical coaches) for their strong support and making this experiment possible.

## REFERENCES

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., and Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J. Appl. Physiol.* 93, 1318–1326. doi: 10.1152/japplphysiol.00283.2002

Abe, T., Kawakami, Y., Ikegawa, S., Kanehisa, H., and Fukunaga, T. (1992). Isometric and isokinetic knee joint performance in Japanese alpine ski racers. *J. Sports Med. Phys. Fitness* 32, 353–357.

Akutsu, T., Kiryu, T., Ushiyama, Y., and Murayama, T. (2008). Evaluation of functional activities during skiing exercise by knee joint angles and surface EMG signals. *Trans. Soc. Instrum. Control Eng.* 44, 905–910. doi: 10.9746/ve.sicetr1965.44.905

Amann, M., and Calbet, J. A. L. (2008). Convective oxygen transport and fatigue. *J. Appl. Physiol.* 104, 861–870. doi: 10.1152/japplphysiol.01008.2007

Bell, D. G. (1993). The influence of air temperature on the EMG/force relationship of the quadriceps. *Eur. J. Appl. Physiol.* 67, 256–260. doi: 10.1007/BF00864225

Bere, T., Flørenes, T. W., Krosshaug, T., Haugen, P., Svandal, I., Nordsletten, L., et al. (2014). A systematic video analysis of 69 injury cases in world cup alpine skiing. *Scand. J. Med. Sci. Sports* 24, 667–677. doi: 10.1111/sms.12038

Bere, T., Flørenes, T. W., Krosshaug, T., Koga, H., Nordsletten, L., Irving, C., et al. (2011). Mechanisms of anterior cruciate ligament injury in world cup alpine skiing: a systematic video analysis of 20 cases. *Am. J. Sports Med.* 39, 1421–1429. doi: 10.1177/0363546511405147

Berg, H. E., and Eiken, O. (1999). Muscle control in elite alpine skiing. *Med. Sci. Sports Exerc.* 31, 1065–1067. doi: 10.1097/00005768-199907000-00022

Billaut, F., Kerris, J. P., Rodriguez, R. F., Martin, D. T., Gore, C. J., and Bishop, D. J. (2013). Interaction of central and peripheral factors during repeated sprints at different levels of arterial O2 saturation. *PLoS One* 8:e77297. doi: 10.1371/journal.pone.0077297

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scand. J. Work Environ. Health* 16(Suppl. 1), 55–58. doi: 10.5271/sjweh.1815

Burtscher, M., Pühringer, R., Werner, I., Sommersacher, R., and Nachbauer, W. (2009). "Predictors of falls in downhill skiing and snowboarding," in *Science and Skiing IV*, eds E. Müller, S. Lindinger, and T. Stöggl (Aachen: Meyer & Meyer Sport), 183–187.

Calbet, J. A., De Paz, J. A., Garatachea, N., Cabeza de Vaca, S., and Chavarren, J. (2003). Anaerobic energy provision does not limit wingate exercise performance in endurance-trained cyclists. *J. Appl. Physiol.* 94, 668–676. doi: 10.1152/japplphysiol.00128.2002

Chapman, R. F., Stickford, J. L., and Levine, B. D. (2010). Altitude training considerations for the winter sport athlete. *Exp. Physiol.* 95, 411–421. doi: 10.1113/expphysiol.2009.050377

Christian, R. J., Bishop, D. J., Billaut, F., and Girard, O. (2014). Peripheral fatigue is not critically regulated during maximal, intermittent, dynamic leg extensions. *J. Appl. Physiol.* 117, 1063–1073. doi: 10.1152/japplphysiol.00988.2013

De Blasi, R. A., Cope, M., Elwell, C., Safoue, F., and Ferrari, M. (1993). Noninvasive measurement of human forearm oxygen consumption by near infrared spectroscopy. *Eur. J. Appl. Physiol.* 67, 20–25. doi: 10.1007/BF00377698

De Blasi, R. A., Ferrari, M., Natali, A., Conti, G., Mega, A., and Gasparetto, A. (1994). Noninvasive measurement of forearm blood flow and oxygen consumption by near-infrared spectroscopy. *J. Appl. Physiol.* 76, 1388–1393. doi: 10.1152/jappl.1994.76.3.1388

DeLorey, D. S., Kowalchuk, J. M., and Paterson, D. H. (2005). Adaptation of pulmonary O2 uptake kinetics and muscle deoxygenation at the onset of heavy-intensity exercise in young and older adults. *J. Appl. Physiol.* 98, 1697–1704. doi: 10.1152/japplphysiol.00607.2004

Edman, K. A., and Josephson, R. K. (2007). Determinants of force rise time during isometric contraction of frog muscle fibres. *J. Physiol.* 580, 1007–1019. doi: 10.1113/jphysiol.2006.119982

Enoka, R. M. (2002). "Movement forces," in *Neuromechanics of Human Movement*, 3rd Edn, (Champaign, IL: Human Kinetics), 57–118.

Ferguson, R. A. (2010). Limitations to performance during alpine skiing. *Exp. Physiol.* 95, 404–410. doi: 10.1113/expphysiol.2009.047563

Ferrari, M., Binzoni, T., and Quaresima, V. (1997). Oxidative metabolism in muscle. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 352, 677–683. doi: 10.1098/rstb.1997.0049

Folland, J. P., Buckthorpe, M. W., and Hannah, R. (2014). Human capacity for explosive force production: neural and contractile determinants. *Scand. J. Med. Sci. Sports* 24, 894–906. doi: 10.1111/sms.12131

Girard, O., Brocherie, F., and Millet, G. P. (2016). High altitude increases alteration in maximal torque but not in rapid torque development in knee extensors after repeated treadmill sprinting. *Front. Physiol.* 7:97. doi: 10.3389/fphys.2016.00097

Girard, O., and Millet, G. (2009). Maximajl rate of force development can represent a more functional measure of muscle activation. *J. Appl. Physiol.* 107, 359–360; discussion 367–368.

Goodall, S., González-Alonso, J., Ali, L., Ross, E. Z., and Romer, L. M. (2012). Supraspinal fatigue after normoxic and hypoxic exercise in humans. *J. Physiol.* 590, 2767–2782. doi: 10.1113/jphysiol.2012.228890

Goodall, S., Ross, E. Z., and Romer, L. M. (2010). Effect of graded hypoxia on supraspinal contributions to fatigue with unilateral knee-extensor contractions. *J. Appl. Physiol.* 109, 1842–1851. doi: 10.1152/japplphysiol.00458.2010

Gruet, M., Temesi, J., Rupp, T., Levy, P., Verges, S., and Millet, G. Y. (2014). Dynamics of corticospinal changes during and after high-intensity quadriceps exercise. *Exp. Physiol.* 99, 1053–1064. doi: 10.1113/expphysiol.2014.078840

Haaland, B., Steenstrup, S. E., Bere, T., Bahr, R., and Nordsletten, L. (2016). Injury rate and injury patterns in FIS world cup alpine skiing (2006-2015): have the new ski regulations made an impact? *Br. J. Sports Med.* 50, 32–36. doi: 10.1136/bjsports-2015-095467

Heitkamp, H. C. (2015). Training with blood flow restriction. mechanisms, gain in strength and safety. *J. Sports Med. Phys. Fitness* 55, 446–456.

Inness, M. W. H., Billaut, F., Walker, E. J., Petersen, A. C., Sweeting, A. J., and Aughey, R. J. (2016). Heavy resistance training in hypoxia enhances 1RM squat performance. *Front. Physiol.* 7:502. doi: 10.3389/fphys.2016.00502

Jordan, M. J., Aagaard, P., and Herzog, W. (2015). Rapid hamstrings/quadriceps strength in ACL-reconstructed elite alpine ski racers. *Med. Sci. Sports Exerc.* 47, 109–119. doi: 10.1249/MSS.0000000000000375

Jordan, M. J., Aagaard, P., and Herzog, W. (2017). Anterior cruciate ligament injury/reinjury in alpine ski racing: a narrative review. *Open Access J. Sports Med.* 8, 71–83. doi: 10.2147/OAJSM.S106699

Kawahara, Y., Saito, Y., Kashimura, K., and Muraoka, I. (2008). Relationship between muscle oxygenation kinetics and the rate of decline in peak torque during isokinetic knee extension in acute hypoxia and normoxia. *Int. J. Sports Med.* 29, 379–383. doi: 10.1055/s-2007-965567

Kiryu, T., Murayama, T., and Ushiyama, Y. (2011). Influence of muscular fatigue on skiing performance during parallel turns. *Conf. Proc. IEEE Eng. Med. Biol. Soc.* 2011, 8187–8190. doi: 10.1109/IEMBS.2011.6092019

Koller, A., Fuchs, B., Leichtfried, V., and Schobersberger, W. (2015). Decrease in eccentric quadriceps and hamstring strength in recreational alpine skiers after prolonged skiing. *BMJ Open Sport Exerc. Med.* 1:bmjsem-2015-000028. doi: 10.1136/bmjsem-2015-000028

Kröll, J., Müller, E., Seifert, J. G., and Wakeling, J. M. (2011). Changes in quadriceps muscle activity during sustained recreational alpine skiing. *J. Sports Sci. Med.* 10, 81–92.

Kröll, J., Seifert, J., Scheiber, P., Schwameder, H., and Müller, E. (2005). "Muscle fatigue in alpine skiing: determination through phase shifting in EMG?" in *Proceedings of the European College of Sports Science*, eds N. Dikic, S. Zivanic, S. Ostojic, and Z. Tornjanski, Belgrade, 178–179.

Lloyd, A., Raccuglia, M., Hodder, S., and Havenith, G. (2016). Interaction between environmental temperature and hypoxia on central and peripheral fatigue during high-intensity dynamic knee extension. *J. Appl. Physiol.* 120, 567–579. doi: 10.1152/japplphysiol.00876.2015

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., and Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *Eur. J. Appl. Physiol.* 116, 1091–1116. doi: 10.1007/s00421-016-3346-6

Matsushita, K., Homma, S., and Okada, E. (1998). Influence of adipose tissue on muscle oxygenation measurement with an NIRS instrument. *Proc. SPIE* 3194, 159–166. doi: 10.1117/12.301048

Millet, G. P., Faiss, R., and Pialoux, V. (2012). Point: hypobaric hypoxia induces different physiological responses from normobaric hypoxia. *J. Appl. Physiol.* 112, 1783–1784. doi: 10.1152/japplphysiol.00067.2012

Morel, B., Rouffet, D. M., Saboul, D., Rota, S., Clémençon, M., and Hautier, C. A. (2015). Peak torque and rate of torque development influence on repeated maximal exercise performance: contractile and neural contributions. *PLoS One* 10:e0119719. doi: 10.1371/journal.pone.0119719

Perrey, S., Racinais, S., Saimouaa, K., and Girard, O. (2010). Neural and muscular adjustments following repeated running sprints. *Eur. J. Appl. Physiol.* 109, 1027–1036. doi: 10.1007/s00421-010-1445-3

Pua, Y.-H., Mentiplay, B. F., Clark, R. A., and Ho, J.-Y. (2017). Associations among quadriceps strength and rate of torque development 6 weeks post anterior cruciate ligament reconstruction and future hop and vertical jump performance: a prospective cohort study. *J. Orthop. Sports Phys. Ther.* 47, 845–852. doi: 10.2519/jospt.2017.7133

Pujol, N., Blanchi, M. P. R., and Chambat, P. (2007). The incidence of anterior cruciate ligament injuries among competitive Alpine skiers: a 25-year investigation. *Am. J. Sports Med.* 35, 1070–1074. doi: 10.1177/0363546507301083

Racinais, S. (2013). Hot ambient conditions shift the force / EMG relationship. *Springerplus* 2:317. doi: 10.1186/2193-1801-2-317

Racinais, S., Gaoua, N., Mtibaa, K., Whiteley, R., Hautier, C., and Alhammoud, M. (2017). Effect of cold on proprioception and cognitive function in elite alpine skiers. *Int. J. Sports Physiol. Perform.* 12, 69–74. doi: 10.1123/ijspp.2016-0002

Ramos-Campo, D. J., Martínez-Guardado, I., Olcina, G., Marín-Pagán, C., Martínez-Noguera, F. J., Carlos-Vivas, J., et al. (2018a). Effect of high-intensity resistance circuit-based training in hypoxia on aerobic performance and repeat sprint ability. *Scand. J. Med. Sci. Sports* doi: 10.1111/sms.13223 [Epub ahead of print].

Ramos-Campo, D. J., Scott, B. R., Alcaraz, P. E., and Rubio-Arias, J. A. (2018b). The efficacy of resistance training in hypoxia to enhance strength and muscle growth: a systematic review and meta-analysis. *Eur. J. Sport Sci.* 18, 92–103. doi: 10.1080/17461391.2017.1388850

Rundell, K. W., Nioka, S., and Chance, B. (1997). Hemoglobin/myoglobin desaturation during speed skating. *Med. Sci. Sports Exerc.* 29, 248–258. doi: 10.1097/00005768-199702000-00014

Rupp, T., Racinais, S., Bringard, A., Lapole, T., and Perrey, S. (2015). Modulation of exercise-induced spinal loop properties in response to oxygen availability. *Eur. J. Appl. Physiol.* 115, 471–482. doi: 10.1007/s00421-014-3032-5

Sangnier, S., and Tourny-Chollet, C. (2008). Study of the fatigue curve in quadriceps and hamstrings of soccer players during isokinetic endurance testing. *J. Strength Cond. Res.* 22, 1458–1467. doi: 10.1519/JSC.0b013e318181ab41

Szmedra, L., Im, J., Nioka, S., Chance, B., and Rundell, K. W. (2001). Hemoglobin/myoglobin oxygen desaturation during Alpine skiing. *Med. Sci. Sports Exerc.* 33, 232–236. doi: 10.1097/00005768-200102000-00010

Tesch, P., Larsson, L., Eriksson, A., and Karlsson, J. (1978). Muscle glycogen depletion and lactate concentration during downhill skiing. *Med. Sci. Sports* 10, 85–90.

Tesch, P. A., and Wright, J. E. (1983). Recovery from short term intense exercise: its relation to capillary supply and blood lactate concentration. *Eur. J. Appl. Physiol.* 52, 98–103. doi: 10.1007/BF00429033

Tillin, N. A., Jimenez-Reyes, P., Pain, M. T. G., and Folland, J. P. (2010). Neuromuscular performance of explosive power athletes versus untrained individuals. *Med. Sci. Sports Exerc.* 42, 781–790. doi: 10.1249/MSS.0b013e3181be9c7e

Tillin, N. A., Pain, M. T. G., and Folland, J. (2013). Explosive force production during isometric squats correlates with athletic performance in rugby union players. *J. Sports Sci.* 31, 66–76. doi: 10.1080/02640414.2012.720704

Tomazin, K., Dolenec, A., and Strojnik, V. (2008). High-frequency fatigue after alpine slalom skiing. *Eur. J. Appl. Physiol.* 103, 189–194. doi: 10.1007/s00421-008-0685-y

Turnbull, J. R., Kilding, A. E., and Keogh, J. W. L. (2009). Physiology of alpine skiing. *Scand. J. Med. Sci. Sports* 19, 146–155. doi: 10.1111/j.1600-0838.2009.00901.x

Ushiyama, Y., Chigira, T., Murayama, T., and Kiryu, T. (2005). Muscle fatigue evaluation system applicable while skiing using EMG and knee joint angles. *Trans. Jpn. Soc. Med. Biol. Eng.* 43, 616–622. doi: 10.11239/jsmbe.43.616

Wittekind, A. L., Micklewright, D., and Beneke, R. (2011). Teleoanticipation in all-out short-duration cycling. *Br. J. Sports Med.* 45, 114–119. doi: 10.1136/bjsm.2009.061580

Zhou, S., Carey, M. F., Snow, R. J., Lawson, D. L., and Morrison, W. E. (1998). Effects of muscle fatigue and temperature on electromechanical delay. *Electromyogr. Clin. Neurophysiol.* 38, 67–73.

Zoladz, J. A., Semik, D., Zawadowska, B., Majerczak, J., Karasinski, J., Kolodziejski, L., et al. (2005). Capillary density and capillary-to-fibre ratio in vastus lateralis muscle of untrained and trained men. *Folia Histochem. Cytobiol.* 43, 11–17.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 18 October 2018
doi: 10.3389/fphys.2018.01485

Check for updates

# Acute Effects of an Ergometer-Based Dryland Alpine Skiing Specific High Intensity Interval Training

*Thomas Stöggl[1]*, Josef Kröll[1,2], Roland Helmberger[1], Maria Cudrigh[2] and Erich Müller[1,2]*

[1] *Department of Sport and Exercise Science, University of Salzburg, Salzburg, Austria,* [2] *Olympic Training Center Salzburg-Rif, Salzburg, Austria*

**Introduction:** To establish an alpine ski racing (ASR) specific dryland high intensity training protocol (HIT), we set out to analyze cardiorespiratory and metabolic responses of three ASR specific HIT modes using a ski ergometer compared with a running HIT.

**Methods:** Ten healthy international FIS level subjects (18 ± 1 years) performed an incremental running $VO_{2max}$ test, three different ASR specific HIT modes [slalom (SL), giant slalom (GS), and SL/GS mix] and a running HIT with measurements of $VO_2$, heart rate (HR), blood lactate, and rate of perceived exertion (RPE). The HIT protocols included 15 × 1-min intervals with >90% $HR_{max}$ and 30 s active rest. Furthermore, one elite alpine skier performed an 8-week, 17 session HIT block using the SL/GS mixed mode.

**Results:** Running HIT resulted in greater $VO_{2peak}$ and whole-body RPE compared with the three ASR-specific HIT modes. During all four exercise modes participants were able to reach exercise intensities high enough to be classified as HIT (>90% $HR_{max}$ and >89% $VO_{2max}$). Legs RPE was similar between the four HIT modes, while arms RPE was higher for the ski-specific HIT. For all studied parameters, similar results for the three skiing specific HIT modes were observed. The 8-week HIT block was feasible for the athlete and resulted in an 11% increase in $VO_{2max}$ at unchanged peak power output.

**Conclusion:** Across all HIT protocols high cardiorespiratory and metabolic responses were achieved. Therefore, the ASR specific HIT was shown to be feasible, thus could offer new possibilities for endurance training in elite alpine skiers. It is suggested to use the SL/GS mixed mode in terms of movement variety. The reduced $VO_2$ in the ski-specific modifications can be attributed to the concentric and eccentric muscle activity resulting in mechanical hindrance for $O_2$ extraction. The long-term effectiveness of ASR specific HIT in elite alpine skiers needs to be proven in a future study.

**Keywords: blood lactate, cardiorespiratory response, giant slalom, RPE, slalom, ski ergometer, specific testing**

OPEN ACCESS

***Edited by:***
*Nicolas Coulmy,*
*Fédération Française de Ski, France*

***Reviewed by:***
*Hannes Gatterer,*
*Eurac Research, Italy*
*Jacques Prioux,*
*Normal Superior School of Rennes, France*

****Correspondence:***
*Thomas Stöggl*
*thomas.stoeggl@sbg.ac.at*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *28 April 2018*
***Accepted:*** *01 October 2018*
***Published:*** *18 October 2018*

***Citation:***
*Stöggl T, Kröll J, Helmberger R, Cudrigh M and Müller E (2018) Acute Effects of an Ergometer-Based Dryland Alpine Skiing Specific High Intensity Interval Training. Front. Physiol. 9:1485. doi: 10.3389/fphys.2018.01485*

## INTRODUCTION

Alpine ski racing (ASR) consists of competition runs of 45 s [e.g., slalom (SL)] up to 2.5 min (e.g., downhill) and can be categorized as high-intensity short-term endurance exercise. While technical skiing skills appear to have the greatest effect on performance, the ability to continually exhibit technical competence within a race but also through a long competitive season requires high capabilities within all physiological systems (Müller et al., 2000; Gross et al., 2009; Turnbull et al., 2009). In this context it was demonstrated that the energy contribution during ASR is based 30–65% on anaerobic and 35–70% on aerobic processes (Veicsteinas et al., 1984; Saibene et al., 1985; Andersen and Montgomery, 1988; Tesch, 1995; Grenier et al., 2013).

Maximal to near maximal heart rate (HR) values (88.9–102.5% of $HR_{max}$; e.g., with respect to maximal HR values achieved during incremental tests to exhaustion with running or in comparison to the theoretical calculated value based on the equation 220-age) are typically attained by the end of the race in either of the four ski disciplines SL, Giant Slalom (GS), Super-G and Downhill (Karlsson et al., 1978; Veicsteinas et al., 1984; Tesch, 1995; Vogt et al., 2005; Grenier et al., 2013; Polat, 2016). However, there is discrepancy with respect to the peak oxygen uptake ($VO_{2peak}$) reached during a run (Karlsson et al., 1978; Saibene et al., 1985; Tesch, 1995; Vogt et al., 2005; Grenier et al., 2013) with documented values between 64% in youth ASR (Grenier et al., 2013) up to 100% in the elite ASR (Tesch, 1995). The most recent study by Polat (2016) depicted 75% of $VO_{2max}$ during GS skiing. Blood lactate concentration of 5.7 mmol $L^{-1}$ on junior level and up to 13 mmol $L^{-1}$ on elite level have been reported for the SL and GS disciplines (Andersen and Montgomery, 1988; Vogt et al., 2000; Grenier et al., 2013; Polat, 2016).

High intensity training (HIT) was demonstrated to be a time efficient alternative to traditional continuous endurance training (Gibala et al., 2012), inducing similar or even superior changes in numerous physiological, performance and health-related markers (e.g., Tabata et al., 1996; Helgerud et al., 2007; Wisloff et al., 2007; Gibala et al., 2012; Stöggl and Sperlich, 2014, 2015; Ni Cheilleachair et al., 2017). More specifically, HIT was shown to increase both the aerobic and anaerobic capacity (Tabata et al., 1996; Ratel et al., 2004; Gibala et al., 2006; Stöggl and Björklund, 2017) which might be of special interest for ASR as shown above. Finally, it was suggested that HIT might be more enjoyable than continuous endurance training (Tjonna et al., 2008; Bartlett et al., 2011; Lambrick et al., 2016). Therefore, HIT concepts receive special attention in sports where the time available to perform a high volume of endurance training is limited (e.g., during games sports, or based on the complex needs in ASR). For ASR, previously it was demonstrated that a short-duration HIT block (e.g., a 2 weeks shock-cycle or motor-block) was feasible and efficient to increase the $VO_{2max}$ with 4.3–6% (Breil et al., 2010; Gross et al., 2014). It should be noted, that in both studies HIT was mainly carried out with non-skiing specific modalities like cycling or running and an obstacle course containing SL running, balancing and jumping elements.

In high performance sports, it has been suggested that improving in the quality of training is more effective in enhancing performance than just increasing the quantity of training. Several studies have suggested that testing (Mygind et al., 1991; Bilodeau et al., 1995; Helgerud et al., 2001; Stöggl et al., 2006) as well as training (Dudley and Djamil, 1985; Hakkinen and Komi, 1986; Hoff et al., 1999) should be sport specific. In specific training, the "principle of kinematic, kinetic, and neuromuscular correspondence" should be taken into consideration. This principle states that the special exercises must be in similar to those parameters of movement that characterize the structure of competition technique (Djatschkow, 1977; Menzel, 1990; Müller et al., 2000). Therefore, the specificity during training should provide coordinative affinity between training exercises and competition which results in favorable training stimuli in the relevant musculature (Müller et al., 2000).

To develop aerobic and anaerobic capacity of alpine skiers on snow, HIT would theoretically be such a specific training mode. It was recently demonstrated that by using short-radius turns during skiing, HIT efforts (>90% $HR_{max}$ and $VO_2$ values >84% $VO_{2max}$) were possible (Stöggl et al., 2016a,b, 2017). However, the drawback to this approach is that on-snow skiing is not feasible, especially during summer, or in combination with high altitude during training phases on the glaciers. For conditioning purposes ASR specific dryland exercises may be better suited for this purpose.

Sport-specific exercises have been used in ASR with different purposes like inline skating for technical training (Zeglinksi et al., 1998; Kröll et al., 2005), specific strength training via an eccentric bike (Gross et al., 2010), or functional training by different ski ergometers (Spitzenpfeil et al., 2005; Panizzolo et al., 2013). Specific endurance training, and more specifically specific HIT, was up to now only mentioned as tool for some training sessions (three sessions out of 15; ski-specific obstacle running course) (Breil et al., 2010). Especially the ski ergometers used by Spitzenpfeil et al. (2005) and Panizzolo et al. (2013) could serve as a tool to perform controlled AS-specific HIT as they fulfill two important criteria: (1) external control of the applied load, and (2) ski specific movement instructions, based on biomechanical studies in ASR (Kröll et al., 2015a,b).

Therefore, the aims of the current study were threefold: (1) to develop different ASR specific dryland HIT protocols on a commercially available ski ergometer and to compare these with a running HIT session using physiological parameters and rating of perceived exertion (RPE); (2) determine the ski specific HIT mode, that complies best with the requirements of a HIT (e.g., intensity > 90% $HR_{max}$), and (3) test the feasibility of a specific HIT block over 2 months with 17 training sessions as a preparation for the Pyeongchang Winter Olympics 2018 as a pilot study. We hypothesized that (a) with the ASR specific HIT protocols the intensities complying for HIT are possible and (b) with HIT using running higher physiological response will be achieved compared with the ASR specific HIT concepts.

## MATERIALS AND METHODS

### Participants

Ten male junior alpine skiers were recruited from a regional Ski Gymnasium to take part in the study. Participants' characteristics are presented in **Table 1**. The participants were healthy and competed on an international (FIS races) level. Participants and their parents were fully informed about the study details and participation requirements with written and verbal information before providing written informed consent to participate. The study received approval from the local Ethics Committee and

**TABLE 1 |** Characteristics of participants without dropouts at baseline examination (mean ± SD [Min; Max]).

| | |
|---|---|
| Age (years) | 18 ± 1 [17; 19] |
| Body height (cm) | 190 ± 6 [171; 190] |
| Body weight (kg) | 76 ± 9 [57.2; 88.0] |
| $VO_{2max}$ (L $min^{-1}$) | 4.4 ± 0.4 [3.5; 5.0] |
| $VO_{2max}$ (ml $kg^{-1}$ $min^{-1}$) | 57.7 ± 3.7 [50.8; 62.7] |
| $HR_{max}$ (bpm) | 199 ± 8 [189; 218] |
| Peak blood lactate (mmol $L^{-1}$) | 11 ± 2 [8.4; 13.4] |
| FIS points slalom | 40.4 ± 15.8 [15.8; 71.0] |
| FIS points giant slalom | 40.8 ± 13.4 [16.1; 60.6] |

*$VO_{2max}$, maximal oxygen consumption; $HR_{max}$, maximal heart rate; FIS, Fédération International de Ski.*

was conducted in accordance with the Declaration of Helsinki. One participant was not able to perform all test trials based on a meniscal injury during ASR training within the period of the study.

## Overall Design

Following the recruiting process every participant underwent six visits on separate days within 2 weeks during the conditioning period (June-July): (1) a $VO_{2max}$ test running on a 400-m level outdoor track, (2) a familiarization HIT session on the ski ergometer for each of the three simulated skiing modes [that is: GS, SL, and a GS–SL mixed mode (GS/SL)], and (3) the four HIT sessions with running, GS, SL and GS/SL mixed in randomized order on four separate days with a minimum of 48 h in between. During the $VO_{2max}$ test and each HIT session $VO_2$, HR, blood lactate, RPE (BORG scale: 6–20) for the whole body ($RPE_{whole-body}$), legs only ($RPE_{legs}$), and arms only ($RPE_{arms}$) were recorded. For standardization purposes, food intake was not permitted 4 h prior to testing and participants were instructed not to change their diet and amount of physical activity throughout the examination period. Furthermore, for all testing days, participants were asked to report well-hydrated and to refrain from consuming alcohol and engaging in strenuous exercise at least 24 h prior to testing.

## Ski Ergometer

A portable ski ergometer was employed for the ASR specific dryland imitation. The ergometer is based on a commercially available simulator (Pro Ski Simulator – Trgovina in storitve, Rače, Slovenia). The ergometer is equipped with six elastic bands that can be used for regulating the load during the exercise. The basic unit was reinforced to resist the high mechanical stress and assembled with a custom-manufactured slide board. The slide board was modified with an alpine ski binding to train more ski specifically. The bindings were mounted on a plate which served to lift the respective "inside heel" in order to enable ski specific knee and hip angulation (Supej, 2010). Compared with the commercial slide board "Pro Ski simulator", the custom-manufactured ergometer was attached with clamping rolls to ensure that the board cannot derail.

The ski-specific motion sequences on the ski ergometer were adapted to the typical on-snow SL and GS techniques based on a pilot study of Kröll et al. (2015b) and previous biomechanical studies (Supej et al., 2011; Spörri et al., 2012): The SL mode is characterized by dynamic movements with a turn cycle duration of 0.83 s and minimum extension knee angles on the outside leg of 90° at turn switch and maximum knee extension angles of about 130° between two turn switches. The GS mode is characterized by a turn cycle duration of 1.41 s and a pronounced quasi-static phase at the end of each leg extension phase. For this mode, similar knee angles to the SL mode were required, although the angles at turn switch seem to be slightly higher in real giant SL skiing (approximately 100° flexion angle). The GS/SL mixed mode alternates every interval GS and SL. To simulate representative lean angles an accompanying knee and hip angulation, participants were instructed to hold the handle bars with their hands in order to freeze the upper body in the center of the device. By doing so, arms, hands and shoulders represented a semi fixed point and just the more distal body regions oscillated against the load of the rubber bands to the left and right. The rhythm of this oscillation was provided by a digital metronome (Tempoperfect Metronome, NCH software, Greenwood Village, CO, United States) based on the above mentioned turn cycle time (SL: 72 bpm; GS: 43 bpm). The skiing specific movement execution, especially appropriate knee and hip angulation and parallel motion of the shank, was controlled by a certificated ski coach among all athletes and modes. The ski-ergometer motion is illustrated in **Figure 1**.

## $VO_{2max}$ Test

The $VO_{2max}$ test was performed on a level 400-m outdoor track. Each subject performed a standardized 10-min warm-up at a running speed of 8 km $h^{-1}$. Subsequently the test protocol started with a speed of 9 km $h^{-1}$ and a 1 km $h^{-1}$ increment every 30 s until exhaustion. Termination criteria were either physical exhaustion, or no longer being able to keep up the running speed of the stage. Running speed was provided by a cyclist driving on the side of the runner. $VO_2$ and HR were measured continuously and a lactate sample was taken during the first, third, and fifth minute upon completion of the test. $VO_{2max}$, $HR_{max}$, peak blood lactate, and peak running speed were determined. This test concept was not separately validated, but is a standard test that is generally applied at our institute for outdoor field tests for establishment of $VO_{2max}$ in various sports (e.g., soccer, alpine skiing, and cross-country skiing) (e.g., Stöggl et al., 2010).

## HIT Protocols

Each of the four HIT sessions began with a 10-min warm-up with an intensity of 70% $HR_{max}$. Participants warmed up running on the track for the running HIT protocol, and cycling on a cycle ergometer for the ski-specific HIT protocols. Each HIT session consisted of 15 bouts of 1 min each, with 30 s of low intensity active breaks, with the goal being to reach an intensity of >90% $HR_{max}$ as quickly as possible. The 1-min interval duration was chosen in accordance with the mean run durations of the technical disciplines SL and GS (Gilgien et al., 2014), and also with reference to comparable HIT protocols presented earlier

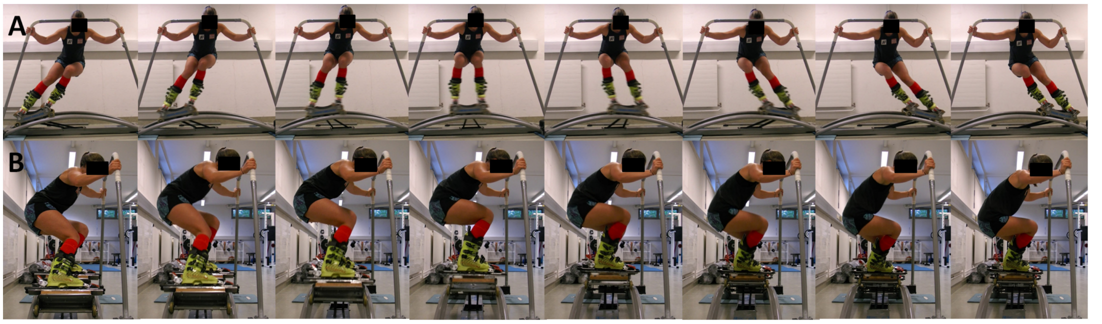


**FIGURE 1 |** Illustrative picture series of the ski-ergometer used for the specific HIT modes giant slalom, slalom and mixed giant slalom-slalom with **(A)** frontal plane view and **(B)** sagittal plane view (Note: written informed consent was obtained from the individual for the publication of this image).

(Hawley and Gibala, 2012; Stöggl et al., 2017). For the running HIT, the intensity was paced by a cyclist (90% of peak speed during the $VO_{2max}$ test) in combination with HR values (target HR of 90–95% $HR_{max}$). Participants walked during the 30-s breaks. To control HR intensity, participants were instructed to reach a HR of 90–95% $HR_{max}$ as quickly as possible. For the ASR specific HIT protocols on the ski-ergometer, the resistance provided by the number of rubber bands used was determined during the familiarization day. As criteria served the highest possible amount of rubber bands during the familiarization day the athlete could compete during repeated 1-min bouts. The 30-s breaks were performed with relaxed side-to-side bouncing on the ski-ergometer in an upright position. $VO_2$ and HR were measured continuously throughout the HIT protocols. Blood lactate was sampled after the 5$^{th}$, 10$^{th}$, and 15$^{th}$ interval and in the third and fifth minute post completion of the HIT protocol. Finally, RPE values for the whole-body, legs and arms were recorded upon completion of the training.

## Instruments

$VO_2$ was continuously recorded by a portable breath-by-breath metabolic cart (K4b$^2$, Cosmed, Italy). The athletes were fitted with a proper sized mask covering the mouth and nose (7450 Series V2$^{TM}$ Mask, Hans Rudolph Inc., Shawnee, KS, United States). Prior to each test trial the gas analyzer's oxygen ($O_2$) and carbon dioxide ($CO_2$) sensors were calibrated using a two-step calibration procedure with ambient air conditions (20.93% $O_2$ and 0.03% $CO_2$) and the anticipated expiratory gas percent using calibration gas containing 15% $O_2$ and 5% $CO_2$ (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany) (rest volume: nitrogen). The flow volume was calibrated using a 3-L syringe. Both calibration procedures were performed directly before each test. Participants' HR was recorded by telemetry (Suunto Ambit 3.0, Helsinki, Finland) sampling at 1-s intervals. For lactate analysis, a 20 μl capillary blood sample from the finger-tip was collected and quantified using an amperometric-enzymatic technique (Biosen S-Line Lab+, EKF-diagnostic GmbH, Magdeburg, Germany). The lactate sensor was calibrated before each test using a lactate standard sample of 12 mmol $L^{-1}$. Results within a range of ±0.1 mmol $L^{-1}$ were accepted.

## Eight Weeks Specific HIT Pilot Study

In a single case study during the conditioning phase (June and July), the feasibility and effects on aerobic capacity of an 8-week HIT block using the ASR specific HIT protocol on the ski-ergometers preparation for the 2018 Olympics was analyzed. One elite AS athlete (age: 25 years; height: 180 cm, weight: 85 kg, FIS points in main disciplines: Downhill 6.5 and Super-G 10.7; overall rank winner of the European Cup 2017/18) volunteered to take part. A $VO_{2max}$ ramp protocol was performed on a cycle ergometer (Ergoline, Ergoselect 100P; Bitz, Germany) before and after (at the end of the second recovery week) the training period. The workload was set at 50 W with a 30 W increase every 30 s until exhaustion. $VO_2$ was measured with a breath-by-breath spirograph as described above.

The training period consisted of two blocks of three training weeks with three HIT sessions/week (first week with only two HIT sessions) interspersed with one recovery week (only one HIT session). In total, the athlete performed 17 HIT sessions. The athlete was instructed to maintain his strength and coordination training during the intervention period. All of the HIT sessions included a 10 min warm-up on a bicycle ergometer at an intensity of 70% $HR_{max}$, followed by the HIT protocol (15 × 1 min at > 90% of $HR_{max}$ with 30-s recovery) alternating between the SL and GS mode between the bouts and a 10-min cool-down on the bicycle ergometer or running. Within each session HR and blood lactate values were collected (5$^{th}$, 10$^{th}$, and 15$^{th}$ interval and in the third and fifth minute post completion of the HIT protocol).

## Statistical Analysis

All data exhibited a Gaussian distribution verified by the Shapiro–Wilk test and accordingly, the values are presented as means (±SD). A one-way ANOVA (four HIT protocols) was performed for each dependent variable with Bonferroni *post hoc* analysis. To compare the progression of the HR, $VO_2$ and blood lactate values across the 15 intervals between the four HIT modes a 3 × 4 ANOVA with repeated measures (3 interval blocks from interval 1–5 vs. 6–10 vs. 11–15; four HIT protocols) was performed. Alpha level of significance was set to 0.05. In addition, the values obtained were evaluated by calculating the effect size ($_p\eta^2$) and statistical power. The Statistical Package for the Social Sciences

(Version 24.0; SPSS Inc., Chicago, IL, United States) was used for statistical analysis.

## RESULTS

### Baseline $VO_{2max}$ Running Test

During the baseline running ramp protocol participants reached a $VO_{2max}$ of 57.7 ± 3.7 ml min$^{-1}$ kg$^{-1}$ (range: 50.8–62.7) with a $HR_{max}$ of 199 ± 8.4 bpm (189–216), and peak blood lactate values of 11.1 ± 1.0 mmol L$^{-1}$ (8.4–13.4).

### Comparison Between Four HIT Protocols

The comparison among the four HIT protocols is presented in **Table 2**. The running HIT achieved higher physiological response in some of the measured variables in comparison to the ASR specific HIT modalities. The main differences were found with respect to cardiorespiratory parameters with higher mean $VO_2$ values in the running HIT protocol compared with all three specific HIT modes ($P = 0.008$). With respect to $VO_{2peak}$ values, running HIT was higher compared with HIT in GS ($P < 0.001$) and SL ($P < 0.01$), while no difference was found to the mixed GS/SL mode. Peak HR trended toward being lower in the GS/SL mixed HIT than the running HIT, although statistical power was low, while no differences were found for mean HR values. Peak blood lactate values was lower with HIT in GS compared with the running HIT ($P < 0.05$). RPE for the whole body was higher in the running HIT when compared with the SL and mixed GS/SL HIT mode. RPE arms was higher in GS and GS/SL mixed mode compared with the running HIT. RPE for the legs was not different between all four HIT modes.

An illustration of the evolution of HR, $VO_2$ and blood lactate values across the 15 1-min intervals within each HIT session is presented in **Figures 2–4**. Interaction effects for time x HIT mode were found for $VO_2$ ($P = 0.029$) and blood lactate ($P = 0.001$) and with a more pronounced increase across the training session in the running HIT compared with the ASR specific HIT protocols.

### Pilot Training Study

**Figure 5** illustrates the development of HR values across the 17 HIT sessions within the 8 weeks training period. All the HIT sessions could be easily performed by the athlete and he was able to reach in all the training sessions a HR > 90% $HR_{max}$, mostly after the 10$^{th}$ interval. Peak blood lactate was 8.1 ± 1.3 mmol L$^{-1}$ (range: 6.5–11.6) across the 17 training sessions. Following the HIT intervention the $VO_{2peak}$ was increased by 11% (Pre: 49.0, Post 54.5 ml min$^{-1}$ kg$^{-1}$) and the peak power output during cycling remained constant at 530 W.

## DISCUSSION

The main findings of the current study are: (1) all four HIT protocols induced sufficient physiological loading to be quantified as HIT (e.g., >90% $HR_{max}$, >88% $VO_{2max}$, blood lactate > 5.9 mmol L$^{-1}$); (2) physiological response with respect to $VO_2$ values was higher in the running HIT compared with the three ASR specific HIT modes; (3) the three ASR specific HIT modes did not differ with respect to the analyzed physiological and RPE values; (4) RPE for the whole body was higher during the running HIT when compared with the specific HIT SL and HIT GS/SL; (5) RPE for the arms was more pronounced in the three ASR specific HIT modes compared with running HIT while no difference was found for RPE legs; and (6) a pilot study in one participant using an ASR specific HIT program over 8 weeks was shown to be feasible and led to an 11% improvement in $VO_{2max}$ with unchanged peak power output during a cycling ramp protocol.

In various measured parameters the running HIT led to higher physiological response compared with the ASR specific HIT modes. This was especially true for the $VO_2$ values and with respect to selected ASR specific modes for HR (e.g., GS/SL mixed), peak blood lactate (GS), and whole-body RPE (SL and GS/SL mixed). However, all four HIT protocols still reached clearly the intensity criteria for being classified as HIT (e.g., Stöggl and Sperlich, 2015) (all four modes: $HR_{peak}$ > 90% $HR_{max}$, $VO_{2peak}$ > 0.88% $VO_{2max}$; blood lactate values >5.9 mmol L$^{-1}$). In addition, the intensity during the specific HIT protocols on the ski-ergometer was comparable with reported values achieved during actual ASR on-snow training and competition. As stated earlier, %$VO_{2max}$ values of 64–100% and %$HR_{max}$ values of 89–102% are documented during ASR (Karlsson et al., 1978; Veicsteinas et al., 1984; Saibene et al., 1985; Tesch, 1995; Vogt et al., 2005; Grenier et al., 2013; Polat, 2016). Specifically, within the three ASR specific HIT modes a pronounced physiological response was attained (95–96% $HR_{max}$ and 88–91% $VO_{2max}$) and participants were able to maintain the intensity across the 15 intervals of each HIT protocol (total duration of 22 min of HIT including the 30 s breaks). Most likely, these high values during the specific HIT modes can just be attained if high strength and coordinative capacities of the athletes are already developed. As demonstrated during ASR, these are the prerequisites of elite alpine athletes to enable them to ski in a very active and exhausting skiing style (Karlsson et al., 1978; Berg and Eiken, 1999; Neumayr et al., 2003).

Except for one significant difference in peak HR between GS/SL mixed HIT vs. running HIT no clear differences in HR could be detected between the four HIT modes. However, this significant difference needs to be assessed critically based on the low statistical power. Based on the high effect size it can be assumed that with a higher sample size the running HIT might have led to higher physiological load also with respect to HR compared with the ASR specific HIT modes. $VO_2$ values were higher in the running HIT protocol – particularly when compared with the pure SL and GS modes. This could possibly be based upon the differences in the mechanics of the muscular work during the running vs. ski specific ski ergometer exercise. Alpine skiing is characterized by a mix of static and dynamic muscle activity of the lower extremities (Müller and Schwameder, 2003; Kröll et al., 2010) with both moderate to high concentric and eccentric loading (Berg et al., 1995; Tesch, 1995; Berg and Eiken, 1999; Kröll et al., 2015a). In contrast to that, mainly dynamic and cyclic muscle loading occurs during other exercises like cycling and running. It might be speculated, that this type

**TABLE 2 |** Cardiorespiratory and metabolic parameters during the high intensity training (HIT) workouts in (1) running, and on the ski ergometer with the three alpine skiing specific exercise modes, (2) giant slalom (GS), (3) slalom (SL), and (4) a mix between GS and SL (mean ± SD) ($n$ = 10).

| | Running | GS | SL | GS/SL mix | ANOVA | | | |
|---|---|---|---|---|---|---|---|---|
| $HR_{mean}$ (bpm) | 182 ± 10 | 175 ± 9 | 175 ± 7 | 173 ± 7 | $F_{3,6}$ = 4.4 | $P$ = 0.058 | $_p\eta^2$ = 0.69 | |
| $HR_{peak}$ (bpm) | 195 ± 11 | 191 ± 12 | 191 ± 9 | 189 ± 9* | $F_{3,6}$ = 5.2 | $P$ = 0.041 | $_p\eta^2$ = 0.72 | pow = 0.67 |
| Rel. $HR_{mean}$ (% $HR_{max}$) | 91 ± 2 | 88 ± 2 | 88 ± 3 | 87 ± 4 | $F_{3,6}$ = 4.5 | $P$ = 0.055 | $_p\eta^2$ = 0.69 | |
| Rel. $HR_{peak}$ (% $HR_{max}$) | 98 ± 2 | 96 ± 3 | 96 ± 3 | 95 ± 3* | $F_{3,6}$ = 5.3 | $P$ = 0.040 | $_p\eta^2$ = 0.73 | pow = 0.67 |
| $VO_{2mean}$ (ml $kg^{-1}$ $min^{-1}$) | 45 ± 3 | 40 ± 4** | 41 ± 3** | 41 ± 4* | $F_{3,6}$ = 10.5 | $P$ = 0.008 | $_p\eta^2$ = 0.84 | pow = 0.93 |
| $VO_{2peak}$ (ml $kg^{-1}$ $min^{-1}$) | 56 ± 3 | 51 ± 4*** | 52 ± 4** | 53 ± 5 | $F_{3,6}$ = 31 | $P$ < 0.001 | $_p\eta^2$ = 0.94 | pow = 1.00 |
| Rel. $VO_{2mean}$ (%$VO_{2max}$) | 79 ± 5 | 68 ± 4** | 71 ± 5** | 70 ± 5* | $F_{3,6}$ = 10.9 | $P$ = 0.008 | $_p\eta^2$ = 0.85 | pow = 0.94 |
| Rel. $VO_{2peak}$ (%$VO_{2max}$) | 97 ± 3 | 88 ± 4*** | 91 ± 4** | 91 ± 5 | $F_{3,6}$ = 32 | $P$ < 0.001 | $_p\eta^2$ = 0.94 | pow = 1.00 |
| Peak blood lactate (mmol $L^{-1}$) | 9.6 ± 2.8 | 6.3 ± 2.2* | 6.5 ± 1.6 | 5.9 ± 1.4 | $F_{3,6}$ = 4.6 | $P$ = 0.053 | $_p\eta^2$ = 0.70 | |
| $RPE_{wholebody}$ | 18.2 ± 0.8 | 16.6 ± 2.0 | 16.3 ± 2.1* | 16.1 ± 1.5** | $F_{3,6}$ = 26 | $P$ = 0.001 | $_p\eta^2$ = 0.93 | pow = 1.00 |
| $RPE_{arms}$ | 13.3 ± 2.2 | 16.4 ± 2.2** | 15.1 ± 2.5 | 16.2 ± 2.2* | $F_{3,6}$ = 6.6 | $P$ = 0.025 | $_p\eta^2$ = 0.77 | pow = 0.77 |
| $RPE_{legs}$ | 16.2 ± 1.6 | 16.6 ± 1.0 | 16.4 ± 1.9 | 15.9 ± 0.9 | $F_{3,6}$ = 1.1 | $P$ = 0.406 | $_p\eta^2$ = 0.36 | |

*HR, heart rate; $VO_2$, oxygen uptake; $VO_{2mean}$, mean oxygen uptake across the HIT protocol; $VO_{2peak}$, peak oxygen uptake within the respective HIT protocol; RPE, rate of perceived exertion; *$P$ < 0.05; **$P$ < 0.01; ***$P$ < 0.001, significantly different to HIT Running; $_p\eta^2$, partial eta square effect size; pow, statistical power.*

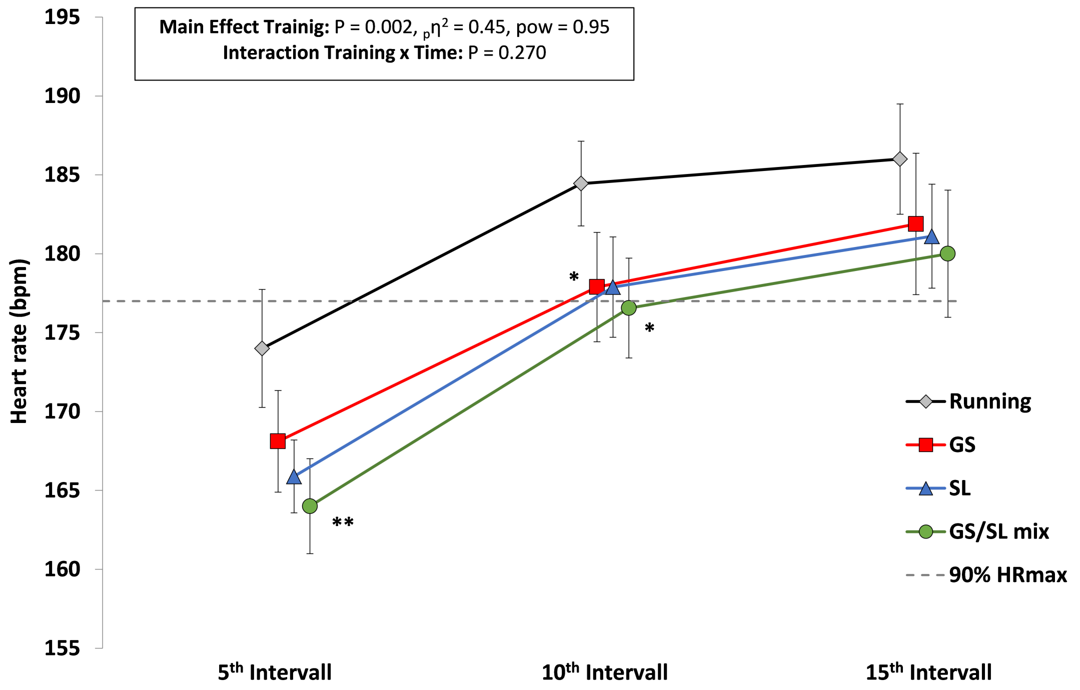


**FIGURE 2 |** Peak heart rate values within interval 1–5 (5th interval), 6–10 (10th interval), and 11–15 (15th interval) for the four HIT protocols with running, giant slalom mode (GS), slalom mode (SL), and the mixed GS/SL mode. *$P$ < 0.05, **$P$ < 0.01, significant different to running; $_p\eta^2$, partial eta square effect size; pow, statistical power; and mean ± SD.

of muscle loading during the ASR imitation exercise resulted in the attenuated increase in cardiorespiratory output based on muscular limitations when compared to running (Stöggl et al., 2016a,b, 2017). In this context, in a study in cross-country skiing it was suggested that $O_2$ extraction can be attenuated based on mechanical hindrance, like magnitude and pattern of force application, muscle activation patterns and time coordination between loading and unloading within a cyclic motion (Stöggl et al., 2013). This attenuation in physiological output could also have been observed in the less pronounced rise in $VO_2$ and blood lactate values during the three ASR specific HIT modes compared with the running HIT (**Figures 1**, **2**). The interaction effects demonstrated that this rise was lower within the first 10 intervals. Therefore, the initial intervals within the ASR specific HIT modes need to be more intense, but merits further analysis.

With respect to the subjective loading of the four HIT protocols, it was found that the legs were equally loaded in all HIT protocols. Whole body RPE was highest during the running HIT, and especially greater compared with the SL and SL/GS HIT modes.

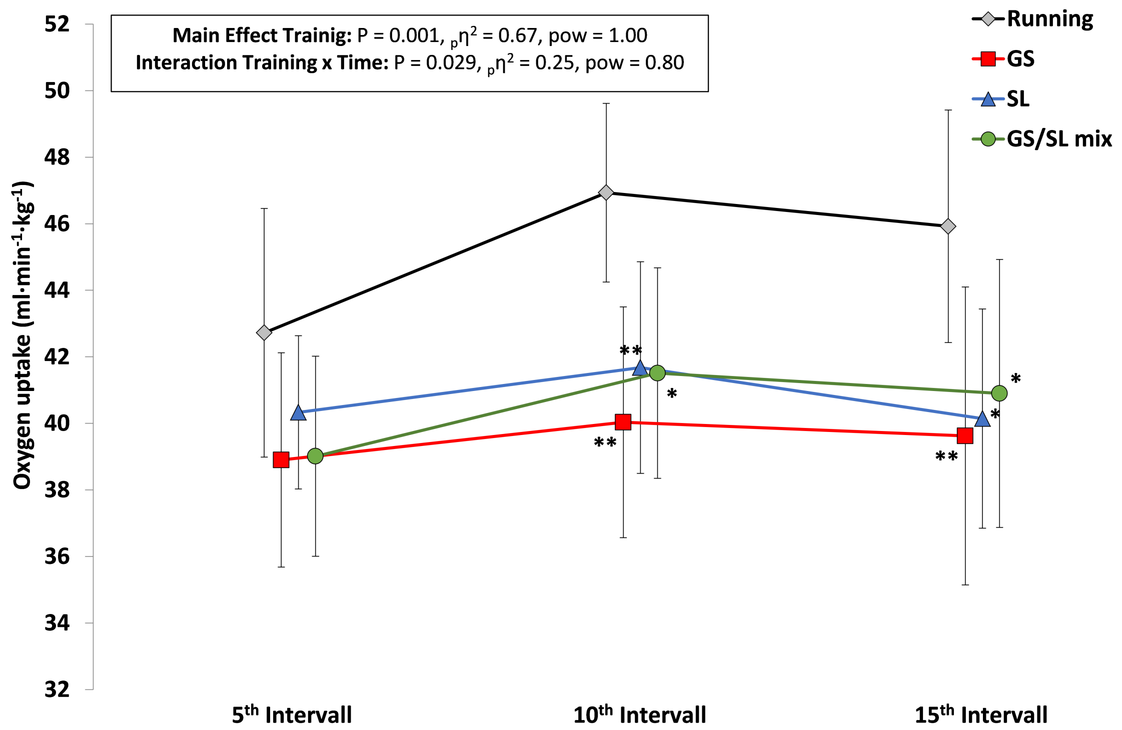


**FIGURE 3 |** Peak $VO_2$ values within interval 1–5 (5th interval), 6–10 (10th interval), and 11–15 (15th interval) for the four HIT protocols with running, giant slalom mode (GS), slalom mode (SL), and the mixed GS/SL mode. $^*P < 0.05$, $^{**}P < 0.01$, significant different to running; ${}_p\eta^2$, partial eta square effect size; pow, statistical power; and mean ± SD.

In a study of fit and unfit recreational skiers it was demonstrated that the subjective loading of the legs during alpine skiing was even greater when compared with classical endurance exercises like cross-country skiing and cycling (Stöggl et al., 2016a,b, 2017) – however, no comparison to running was performed. One would presume that a strength-oriented task like the ski ergometer would result in perceived higher demands for the legs compared to the more endurance-oriented task running. ASR athletes usually train their aerobic capacity more on cycle ergometers than with running (Breil et al., 2010), however, they perform a lot of strength and strength endurance training with knee-hip-extension-flexion exercises like squats or jumps in different forms (Patterson et al., 2009). Therefore, the relative inexperience of the ASR athletes in running serves as an explanation for relative high leg RPE values not only for the specific HIT modes but also during running.

The use of the arms during the ski ergometer exercise led to increased arm RPE when compared to the running HIT. The athletes were instructed to hold the handle bars with their hands in order to freeze the upper body in the center of the device. By doing so a simulation of representative lean angles and accompanying knee and hip angulation was possible (Supej, 2010). Therefore, the ski specific exercise leads to a clear loading, and perceived exhaustion of the arms. To create the movement on the ski ergometer (i.e., produce force against the rubber bands), the participants used the arms and the upper body to generate force which was transmitted down the kinetic chain to the skiing platform. Therefore, it seems plausible that this leads to distinct and specific activation of the trunk for the stabilization and control of the motion, especially during the static hold at the end points of the GS mode. With respect to injury prevention the aspect of adequate stimuli for core stability by using the ski-ergometer could be of interest from two perspectives: The prevention of low back pain overuse injuries but also for the prevention of acute knee injuries which both are described as serious problem in ASR (Florenes et al., 2009; Spörri et al., 2015). For both areas insufficient core strength, respectively, stability seems to be a main risk factor. Raschner et al. (2012) suggested that core strength is a predominant critical factor for ACL injuries in young ski racers.

Consequently, the ASR specific ski-ergometer exercise described in the current study might constitute a good combination to specifically train HIT, but also to specifically load and train important structures and muscles for ASR with respect to performance (i.e., high leg RPE values) but also specific injury prevention (core stability). Future research is needed to prove this concept on effectivity in enhancing ASR performance.

All specific HIT modes led to comparable physiological and metabolic loading, whether cycle frequency was high (e.g., SL) or low (e.g., GS) or if these two modes were alternately applied during each consecutive interval (GS/SL mix). Though not statistically significant, $VO_2$ was higher and whole-body RPE

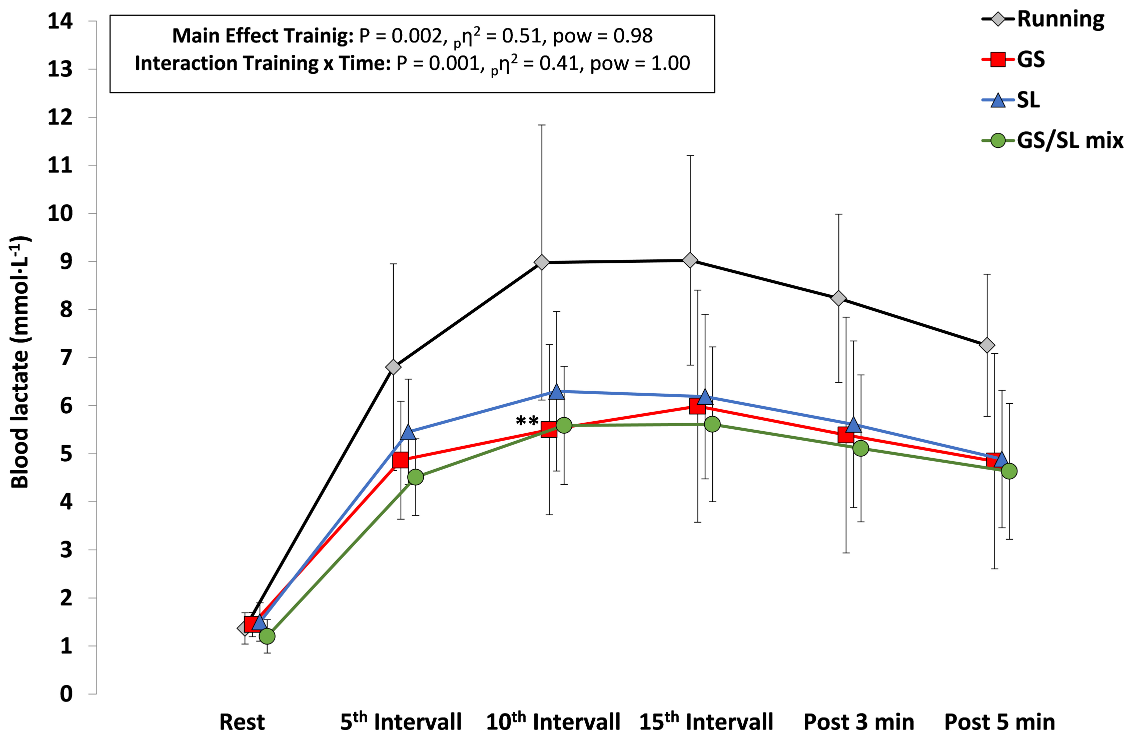


**FIGURE 4 |** Blood lactate values after the 5th, 10th, and 15th interval and in the third and fifth minute post exercise for the four HIT protocols with running, giant slalom mode (GS), slalom mode (SL), and the mixed GS/SL mode. ***P* < 0.01; significant different to running; $_p\eta^2$, partial eta square effect size; pow, statistical power; and mean ± SD.

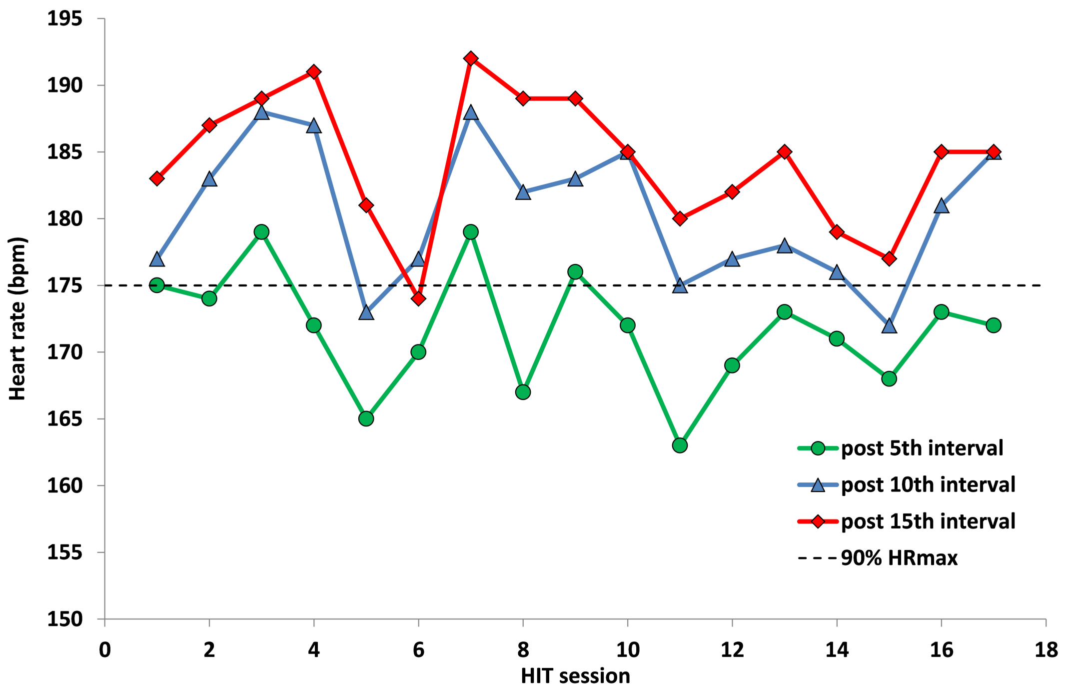


**FIGURE 5 |** Peak heart rate values after the 5th, 10th, and 15th interval across the 17 HIT sessions during the 8-week training period.

lower in the GS/SL mixed mode than the GS or SL HIT. Based on this outcome, as well as the feedback from athletes preferring less monotonously sessions, the GS/SL mixed HIT protocol was applied for a single case pilot training study in one elite ASR skier to check if this training concept is feasible for ASR elite sports. The results demonstrate that the athlete was able to perform all 17 sessions with sufficient physiological response (>90% $HR_{max}$ in every session and mean peak blood lactate values of 8.1 mmol $L^{-1}$), with no marked signs of overloading symptoms. The training led to an 11% increase in the $VO_{2max}$ and unchanged peak power output on the cycle ergometer. Based on these findings, a future study is warranted demonstrating if the implementation of a specific HIT over a longer period of time is effective in increasing aerobic and anaerobic capacity, peak power output and specific strength of the lower body and the trunk when compared with a standard HIT training concept in running or cycling.

## CONCLUSION

The HIT protocol with running resulted in a more pronounced response in $VO_2$ compared with the three ASR specific HIT modes. However, with all four HIT protocols participants were able to reach exercise intensities sufficiently high to be classified as HIT (>90% $HR_{max}$ and >88% $VO_{2max}$). The increased loading of the arms during the ASR specific HIT workouts might be of special interest for training both the aerobic and anaerobic capacity but also upper body and trunk strength, all important aspects or performance and injury prevention in ASR. Consequently, the combination of the ASR specific ergometer with a 15 × 1-min HIT protocol might provide sufficient stimulus for the cardiorespiratory and metabolic systems to enhance aerobic and anaerobic capacity. The effectiveness of such a HIT protocol over longer duration was shown to be feasible in one elite alpine skier. Based on his successful skiing season following this intervention (e.g., winner of the European Cup total ranking in downhill skiing), no negative side-effects on true skiing capabilities can be stated so far. However, the effects of this training protocol on a larger group of elite alpine skiers on aspects of endurance, power and core needs to be proven in a future study. Furthermore, a detailed description of the functional (biomechanical) similarity between the instructed movement on the ski-ergometer and the on-snow situation would complete the picture on how the ergometer could be used best possible in the off-season training of ASR athletes.

## AUTHOR CONTRIBUTIONS

TS, JK, RH, MC, and EM conceived and designed the experiments, and read and approved the final manuscript. JK, RH, and MC performed the experiments. TS, RH, and MC analyzed the data. TS, JK, and RH prepared the manuscript.

## ACKNOWLEDGMENTS

We would like to thank the participants from the Skigymnasium Saalfelden and namely their head coach Thomas Egger for the enthusiasm and cooperation within the project. Furthermore, we would like to thank Johannes Ebner, machine fitter at the Olympic Training Centre Salzburg-Rif, for his support and Cory Snyder for his valuable comments on the manuscript. The current study complies with Austrian ethical standards and laws. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. None of the authors had any personal or financial conflicts of interest.

## REFERENCES

Andersen, R. E., and Montgomery, D. L. (1988). Physiology of alpine skiing. *Sports Med.* 6, 210–221. doi: 10.2165/00007256-198806040-00003

Bartlett, J. D., Close, G. L., Maclaren, D. P., Gregson, W., Drust, B., and Morton, J. P. (2011). High-intensity interval running is perceived to be more enjoyable than moderate-intensity continuous exercise: implications for exercise adherence. *J. Sports Sci.* 29, 547–553. doi: 10.1080/02640414.2010.545427

Berg, H. E., and Eiken, O. (1999). Muscle control in elite alpine skiing. *Med. Sci. Sports Exerc.* 31, 1065–1067. doi: 10.1097/00005768-199907000-00022

Berg, H. E., Eiken, O., and Tesch, P. A. (1995). Involvement of eccentric muscle actions in giant slalom racing. *Med. Sci. Sports Exerc.* 27, 1666–1670. doi: 10.1249/00005768-199512000-00013

Bilodeau, B., Roy, B., and Boulay, M. R. (1995). Upper-body testing of cross-country skiers. *Med. Sci. Sports Exerc.* 27, 1557–1562. doi: 10.1249/00005768-199511000-00013

Breil, F. A., Weber, S. N., Koller, S., Hoppeler, H., and Vogt, M. (2010). Block training periodization in alpine skiing: effects of 11-day HIT on VO2max and performance. *Eur. J. Appl. Physiol.* 109, 1077–1086. doi: 10.1007/s00421-010-1455-1

Djatschkow, W. M. (1977). *Die Steuerung und Optimierung des Trainingsprozesses*. Berlin: Bartels & Wenitz KG.

Dudley, G. A., and Djamil, R. (1985). Incompatibility of endurance- and strength-training modes of exercise. *J. Appl. Physiol.* 59, 1446–1451. doi: 10.1152/jappl.1985.59.5.1446

Florenes, T. W., Bere, T., Nordsletten, L., Heir, S., and Bahr, R. (2009). Injuries among male and female world cup alpine skiers. *Br. J. Sports Med.* 43, 973–978. doi: 10.1136/bjsm.2009.068759

Gibala, M. J., Little, J. P., Macdonald, M. J., and Hawley, J. A. (2012). Physiological adaptations to low-volume, high-intensity interval training in health and disease. *J. Physiol.* 590, 1077–1084. doi: 10.1113/jphysiol.2011.224725

Gibala, M. J., Little, J. P., Van Essen, M., Wilkin, G. P., Burgomaster, K. A., Safdar, A., et al. (2006). Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *J. Physiol.* 575, 901–911. doi: 10.1113/jphysiol.2006.112094

Gilgien, M., Spörri, J., Kröll, J., Crivelli, P., and Müller, E. (2014). Mechanics of turning and jumping and skier speed are associated with injury risk in men's world cup alpine skiing: a comparison between the competition disciplines. *Br. J. Sports Med.* 48, 742–747. doi: 10.1136/bjsports-2013-092994

Grenier, J. G., Hintzy, F., Antichan, F., and Coulmy, N. (2013). Débit énergétique et implications des filières anaérobie lactique et aérobie lors d'un slalom géant chez l'enfant skieur compétiteur. *Sci. Sports* 28, 29–35. doi: 10.1016/j.scispo.2012.06.004

Gross, M. A., Breil, F. A., Lehmann, A. D., Hoppeler, H., and Vogt, M. (2009). Seasonal variation of VO 2 max and the VO2-work rate relationship in elite Alpine skiers. *Med. Sci. Sports Exerc.* 41, 2084–2089. doi: 10.1249/MSS.0b013e3181a8c37a

Gross, M. A., Hemund, K., and Vogt, M. (2014). High intensity training and energy production during 90-second box jump in junior alpine skiers. *J. Strength Cond. Res.* 28, 1581–1587. doi: 10.1519/JSC.0000000000000294

Gross, M. A., Lüthy, F., Kröll, J., Müller, E., Hoppeler, H., and Vogt, M. (2010). Effects of eccentric cycle ergometry in alpine skiers. *Int. J. Sports Med.* 31, 572–576. doi: 10.1055/s-0030-1254082

Hakkinen, K., and Komi, P. V. (1986). Training-induced changes in neuromuscular performance under voluntary and reflex conditions. *Eur. J. Appl. Physiol. Occup. Physiol.* 55, 147–155. doi: 10.1007/BF00714997

Hawley, J. A., and Gibala, M. J. (2012). What's new since Hippocrates? Preventing type 2 diabetes by physical exercise and diet. *Diabetologia* 55, 535–539. doi: 10.1007/s00125-012-2460-1

Helgerud, J., Hoydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., et al. (2007). Aerobic high-intensity intervals improve VO2max more than moderate training. *Med. Sci. Sports Exerc.* 39, 665–671. doi: 10.1249/mss.0b013e3180304570

Helgerud, J., Vik, J. T., and Hoff, J. (2001). The effect of maximal strength training on endurance performance in upper body for highly trained male cross-country skiers. *Corpu, Psyche Soc.* 8, 90–103.

Hoff, J., Helgerud, J., and Wisloff, U. (1999). Maximal strength training improves work economy in trained female cross-country skiers. *Med. Sci. Sports Exerc.* 31, 870–877. doi: 10.1097/00005768-199906000-00016

Karlsson, J., Eriksson, A., Forsberg, A., Kallberg, L., and Tesch, P. A. (1978). *The Physiology of Alpine Skiing*. Stockholm: Trygg-Hansa Insurance Company.

Kröll, J., Schiefermüller, C., Birklbauer, J., and Müller, E. (2005). "Inline-skating as a dry land modality for slalom racers – electromyographic and dynamic similarities and differences," in *Science and Skiing III, Proceedings to the 3rd International Congress on Science and Skiing (ICSS)*, eds E. Müller, D. Bacharach, R. Klika, S. Lindinger, and H. Schwameder (Oxford: Meyer & Meyer Sport Verlag), 76–86.

Kröll, J., Spörri, J., Fasel, B., Müller, E., and Schwameder, H. (2015a). "Type of muscle control in elite alpine skiing – Is it still the same than in 1995?," in *Science and Skiing VI*, eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Aachen: Meyer & Meyer Sport), 56–64.

Kröll, J., Spörri, J., Kandler, C., Fasel, B., Müller, E., and Schwameder, H. (2015b). "Kinetic and kinematic comparison of alpine ski racing disciplines as a base for specific conditioning regimes," in *33rd International Conference on Biomechanics in Sports*, eds M. Colloud, M. Domalain, and T. Monnet, Poitiers.

Kröll, J., Wakeling, J. M., Seifert, J. G., and Müller, E. (2010). Quadriceps muscle function during recreational alpine skiing. *Med. Sci. Sports Exerc.* 42, 1545–1556. doi: 10.1249/MSS.0b013e3181d299cf

Lambrick, D., Westrupp, N., Kaufmann, S., Stoner, L., and Faulkner, J. (2016). The effectiveness of a high-intensity games intervention on improving indices of health in young children. *J. Sports Sci.* 34, 190–198. doi: 10.1080/02640414.2015.1048521

Menzel, H. I. (1990). *Kinematische Affinität von Trainings- und Wettkampfwürfen im Speerwurf*. Frankfurt: Thun & Deutsch.

Müller, E., Benko, U., Raschner, C., and Schwameder, H. (2000). Specific fitness training and testing in competitive sports. *Med. Sci. Sports Exerc.* 32, 216–220. doi: 10.1097/00005768-200001000-00032

Müller, E., and Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J. Sports Sci.* 21, 679–692. doi: 10.1080/0264041031000140284

Mygind, E., Larsson, B., and Klausen, T. (1991). Evaluation of a specific test in cross-country skiing. *J. Sports Sci.* 9, 249–257. doi: 10.1080/02640419108729887

Neumayr, G., Hoertnagl, H., Pfister, R., Koller, A., Eibl, G., and Raas, E. (2003). Physical and physiological factors associated with success in professional alpine skiing. *Int. J. Sports Med.* 24, 571–575. doi: 10.1055/s-2003-43270

Ni Cheilleachair, N. J., Harrison, A. J., and Warrington, G. D. (2017). HIIT enhances endurance performance and aerobic characteristics more than high-volume training in trained rowers. *J. Sports Sci.* 35, 1052–1058. doi: 10.1080/02640414.2016.1209539

Panizzolo, F. A., Marcolin, G., and Petrone, N. (2013). Comparative evaluation of two skiing simulators as functional training devices for recreational skiers. *J. Sports Sci. Med.* 12, 151–158.

Patterson, C., Raschner, C., and Platzer, H. P. (2009). Power variables and bilateral force differences during unloaded and loaded squat jumps in high performance alpine ski racers. *J. Strength Cond. Res.* 23, 779–787. doi: 10.1519/JSC.0b013e3181a2d7b3

Polat, M. (2016). An examination of respiratory and metabolic demands of alpine skiing. *J. Exerc. Sci. Fit.* 14, 76–81. doi: 10.1016/j.jesf.2016.10.001

Raschner, C., Platzer, H. P., Patterson, C., Werner, I., Huber, R., and Hildebrandt, C. (2012). The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. *Br. J. Sports Med.* 46, 1065–1071. doi: 10.1136/bjsports-2012-091050

Ratel, S., Lazaar, N., Dore, E., Baquet, G., Williams, C. A., Berthoin, S., et al. (2004). High-intensity intermittent activities at school: controversies and facts. *J. Sports Med. Phys. Fitness* 44, 272–280.

Saibene, F., Cortili, G., Gavazzi, P., and Magistri, P. (1985). Energy sources in alpine skiing (giant slalom). *Eur. J. Appl. Physiol. Occup. Physiol.* 53, 312–316. doi: 10.1007/BF00422845

Spitzenpfeil, P., Niessen, M., and Hartmann, U. (eds) (2005). *Evaluation of a Specific Training Device in Alpine Skiing*. Aachen: Meyer & Meyer Sport.

Spörri, J., Haid, C., Kröll, J., Jahnel, R., Fasel, B., and Müller, E. (2015). "Prevention of low back overuse injuries in alpine ski racing - what do we know and where do we go from here?," in *Science and Skiing VI*, eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Maidenhead: Meyer & Meyer Sport), 76–86.

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach* 7, 647–659. doi: 10.1260/1747-9541.7.4.647

Stöggl, T., Sageder, T., Stiglbauer, R., and Müller, E. (2010). Hochintensives Intervall- (HIT) und Schnelligkeitstraining im Fußball. *Leistungssport* 40, 43–49.

Stöggl, T. L., and Björklund, G. (2017). High intensity interval training leads to greater improvements in acute heart rate recovery and anaerobic power as high volume low intensity training. *Front. Physiol.* 8:562. doi: 10.3389/fphys.2017.00562

Stöggl, T. L., Björklund, G., and Holmberg, H. C. (2013). Biomechanical determinants of oxygen extraction during cross-country skiing. *Scand. J. Med. Sci. Sports* 23, e9–e20. doi: 10.1111/sms.12004

Stöggl, T. L., Lindinger, S., and Müller, E. (2006). Biomechanical validation of a specific upper body training and testing drill in cross-country skiing. *Sports Biomech.* 5, 23–46. doi: 10.1080/14763141.2006.9628223

Stöggl, T. L., Schwarzl, C., Müller, E. E., Nagasaki, M., Stöggl, J., Scheiber, P., et al. (2016a). A comparison between alpine skiing, cross-country skiing and indoor cycling on cardiorespiratory and metabolic response. *J. Sports Sci. Med.* 15, 184–195.

Stöggl, T. L., Schwarzl, C., Müller, E. E., Nagasaki, M., Stoggl, J., Scheiber, P., et al. (2016b). Effects of skiing on cardiorespiratory and metabolic responses in middle-aged subjects with increased cardiovascular risk. *Int. J. Cardiol.* 203, 618–620. doi: 10.1016/j.ijcard.2015.11.016

Stöggl, T. L., Schwarzl, C., Müller, E. E., Nagasaki, M., Stöggl, J., Schönfelder, M., et al. (2017). Alpine skiing as winter-time high-intensity training. *Med. Sci. Sports Exerc.* 49, 1859–1867. doi: 10.1249/MSS.0000000000001289

Stöggl, T. L., and Sperlich, B. (2014). Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Front. Physiol.* 5:33. doi: 10.3389/fphys.2014.00033

Stöggl, T. L., and Sperlich, B. (2015). The training intensity distribution among well-trained and elite endurance athletes. *Front. Physiol.* 6:295. doi: 10.3389/fphys.2015.00295

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *J. Sports Sci.* 28, 759–769. doi: 10.1080/02640411003716934

Supej, M., Kipp, R., and Holmberg, H. C. (2011). Mechanical parameters as predictors of performance in alpine world cup slalom racing. *Scand. J. Med. Sci. Sports* 21, e72–e81. doi: 10.1111/j.1600-0838.2010.01159.x

Tabata, I., Nishimura, K., Kouzaki, M., Hirai, Y., Ogita, F., Miyachi, M., et al. (1996). Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and VO2max. *Med. Sci. Sports Exerc.* 28, 1327–1330. doi: 10.1097/00005768-199610000-00018

Tesch, P. A. (1995). Aspects on muscle properties and use in competitive Alpine skiing. *Med. Sci. Sports Exerc.* 27, 310–314. doi: 10.1249/00005768-199503000-00004

Tjonna, A. E., Lee, S. J., Rognmo, O., Stolen, T. O., Bye, A., Haram, P. M., et al. (2008). Aerobic interval training versus continuous moderate exercise as a treatment for the metabolic syndrome: a pilot study. *Circulation* 118, 346–354. doi: 10.1161/CIRCULATIONAHA.108.772822

Turnbull, J. R., Kilding, A. E., and Keogh, J. W. (2009). Physiology of alpine skiing. *Scand. J. Med. Sci. Sports* 19, 146–155. doi: 10.1111/j.1600-0838.2009.00901.x

Veicsteinas, A., Ferretti, G., Margonato, V., Rosa, G., and Tagliabue, D. (1984). Energy cost of and energy sources for alpine skiing in top athletes. *J. Appl. Physiol. Respir. Environ. Exerc. Physiol.* 56, 1187–1190.

Vogt, M., Puntschart, A., Angermann, M., Jordan, K., Spring, H., Müller, E., et al. (2005). Metabolische konsequenzen eines wettkampfmäßigen slalomtrainings bei nachwuchs-skiathleten. *Leistungssport* 35, 48–54.

Vogt, M., Rickli, S., Städler, R., Bartsch, D., Spring, H., and Hoppeler, H. (2000). Zur trainingssteuerung im alpinen skirennsport. *Schweizerische Zeitschrift «Sportmedizin Sporttraumatologie* 48, 146–152.

Wisloff, U., Stoylen, A., Loennechen, J. P., Bruvold, M., Rognmo, O., Haram, P. M., et al. (2007). Superior cardiovascular effect of aerobic interval training versus moderate continuous training in heart failure patients: a randomized study. *Circulation* 115, 3086–3094. doi: 10.1161/CIRCULATIONAHA.106.675041

Zeglinksi, C. M., Swanson, S. C., Self, B. P., and Greenwald, R. M. (1998). Muscle activity in the slalom turn of alpine skiing and in-line skating. *Int. J. Sports Med.* 19, 447–454. doi: 10.1055/s-2007-971943

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

PERSPECTIVE
published: 20 February 2019
doi: 10.3389/fphys.2019.00111

Check for updates

# Recent Kinematic and Kinetic Advances in Olympic Alpine Skiing: Pyeongchang and Beyond

*Matej Supej*[1]* *and H.-C. Holmberg*[2,3]

[1] Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia, [2] The Swedish Winter Sports Research Centre, Mid Sweden University, Östersund, Sweden, [3] School of Sport Sciences, UiT The Arctic University of Norway, Tromsø, Norway

Alpine skiing has been an Olympic event since the first Winter Games in 1936. Nowadays, skiers compete in four main events: slalom, giant slalom, super-G and downhill. Here, we present an update on the biomechanics of alpine ski racers and their equipment. The technical and tactical ability of today's world-class skiers have adapted substantially to changes in equipment, snow conditions and courses. The wide variety of terrain, slopes, gate setups and snow conditions involved in alpine skiing requires skiers to continuously adapt, alternating between the carving and skidding turning techniques. The technical complexity places a premium on minimizing energy dissipation, employing strategies and ski equipment that minimize ski-snow friction and aerodynamic drag. Access to multiple split times along the racing course, in combination with analysis of the trajectory and speed provide information that can be utilized to enhance performance. Peak ground reaction forces, which can be as high as five times body weight, serve as a measure of the external load on the skier and equipment. Although the biomechanics of alpine skiing have significantly improved, several questions concerning optimization of skiers' performance remain to be investigated. Recent advances in sensor technology that allow kinematics and kinetics to be monitored can provide detailed information about the biomechanical factors related to success in competitions. Moreover, collection of data during training and actual competitions will enhance the quality of guidelines for training future Olympic champions. At the same time, the need to individualize training and skiing equipment for each unique skier will motivate innovative scientific research for years to come.

**Keywords: downhill, giant slalom, performance, super-G, tactics, technique**



***Edited by:***
*Nicolas Coulmy,*
*Fédération Française de Ski, France*

***Reviewed by:***
*Laurent Mourot,*
*Université Bourgogne Franche-Comté, France*
*Robert Cortas Reid,*
*Norwegian Ski Federation, Norway*
*Gregoire P. Millet,*
*Université de Lausanne, Switzerland*

***Correspondence:***
*Matej Supej*
*Matej.Supej@fsp.uni-lj.si*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *26 April 2018*
***Accepted:*** *30 January 2019*
***Published:*** *20 February 2019*

***Citation:***
*Supej M and Holmberg H-C (2019) Recent Kinematic and Kinetic Advances in Olympic Alpine Skiing: Pyeongchang and Beyond. Front. Physiol. 10:111. doi: 10.3389/fphys.2019.00111*

## INTRODUCTION

Alpine skiing, a physically, technically and tactically complex and challenging sport, has been an Olympic event since the first Winter Games in Garmisch-Partenkirchen, Germany, in 1936. More effective training and advances in equipment and snow preparation have improved the performance of Olympic alpine skiers dramatically since then. Winning margins are now often no more than fractions of a second and biomechanical factors determine which skiers win medals.

This sport involves the technical events slalom (SL) and giant slalom (GS) and speed events super giant slalom (SG) and downhill (DH), each with its own gate placement (and thereby turning radii), terrain, speed, and course length, some of which are regulated by the International Ski Federation (FIS) (Gilgien et al., 2015; Supej et al., 2015; Erdmann et al., 2017). In the case of SL the speed is 40–60 km/h, whereas the maximal speeds in GS, SG and DH average 70 (80), 80 (102), and 86 (120) km/h, respectively (Gilgien et al., 2015). Typical race durations are approximately 2 × 50–60 s for the SL, 2 × 70–90 s for the GS, 1 × 80 s for the Super-G, 1 × 120 s for the DH, 1 × 40–45 s (SL) and 1 × 80–120 s (DH) for the combined event and 4 × 20 s for the team parallel slalom[1]. Official data from the Pyeongchang Olympic Games 2018 are presented in **Table 1**.

To achieve the shortest combined time on all sections of a course and thereby win, the alpine skier should (1) lose as little time as possible on his/her weakest sections and win as much as possible on strong sections or (2) approach the best time on all sections (Supej and Cernigoj, 2006; Hébert-Losier et al., 2014).

The technical complexity involved in continuously adapting turning technique to changes in terrain, slope, gate setup, and snow conditions demands biomechanical analysis of the determinants of elite performance that is more detailed and nuanced than that based on racing time alone (Supej, 2008; Supej et al., 2011; Federolf, 2012; Spörri et al., 2018). This is challenging, since many kinematic and kinetic factors influence performance directly or indirectly (**Figure 1**), including the trajectory of the skis and/or center of mass, turning radius and speed, ground reaction forces (GRF), aerodynamic drag and frictional forces, as well as energy dissipation (i.e., the efficiency of mechanical energy utilization) (Supej et al., 2005, 2011, 2013, 2015; Supej, 2008; Supej and Holmberg, 2010; Federolf, 2012; Meyer et al., 2012; Hébert-Losier et al., 2014; Spörri et al., 2018). In addition, biomechanical differences between the various turning techniques, the inter-dependency of turns, tactics and ski equipment are important considerations in this context (Supej et al., 2002, 2004; Supej and Cernigoj, 2006; Chardonnens et al., 2010).

Our aim here was to provide an update on the biomechanics of alpine ski racers and the equipment they use.

## TURNING TECHNIQUES

Prior to the Winter Olympics in Nagano in 1998, alpine skiers utilized so-called classic skis with a side-cut radius longer than approximately 30 m. For many years short turns around gates with straight skiing between turns was considered optimal for SL and GS. However, already in the 1980s, skiers began striving for so-called clean turns (now known as carving turns). For example, when the movements of Alberto Tomba (the dominant skier in technical events during the late 1980s and 1990s, with gold medals in slalom and giant slalom at the World Championships and Olympic Games) were analyzed on the basis of slow-motion video recordings and images, coaches realized that he placed more pressure on the tails of the skis after the fall line, enabling "carving" (i.e., cutting into the snow, so that the skis bend into an arc and then turn). The translocation of pressure from the forefoot (at the beginning of the turn) toward the heel (at the end of the turn) is still a feature of alpine ski racing (Falda-Buscaiot et al., 2017).

Since the introduction of carving skis, this type of turn was developed further, resulting in novel features such as the "single motion" technique in slalom (Supej et al., 2002, 2004; Müller and Schwameder, 2003) and "cross-under" technique in giant slalom (Chardonnens et al., 2010). With both of these techniques, the posture of the skier's body while transferring weight is more "crunched" than when rounding the gate, which is the opposite of the situation with earlier elite skiers. More specifically, with the "single motion" technique, the skier starts to extend his/her body after the transfer of weight and continues this extension during the early steering phase; flexion of the body begins soon after the fall line; and, finally, the skier is most "crunched" up during the subsequent transfer of weight (Supej et al., 2002, 2004). Such "harmonious" movement incorporates both a single extension and single flexion per each turn. With the "cross-under" technique used in giant slalom, the trunk remains stable during the transfer of weight, with movement of the legs altering the edges of the skis (Chardonnens et al., 2010). In contrast, with the techniques employed traditionally in giant slalom the trunk swings over the legs during the transfer of weight.

For two decades, in attempt to reduce injuries, the FIS has implemented new regulations concerning primarily the side-cut, length and waist width of skis, as well as the nature of the race course (Gilgien et al., 2015, 2016; Haaland et al., 2016; Kröll et al., 2016b,a; Spörri et al., 2016a,b, 2017; Supej et al., 2017). These regulations have influenced technique and tactics significantly, especially in the case of slalom and giant slalom. Consequently, in addition to smooth carving turns, today's elite skiers utilize turns that involve skidding or so-called "free rotation" of the skis during the initiation and/or early steering phase.

## KINEMATICS

### Racing Time

In contrast to the single split time in the 1960s, today's races involve 3–4 split times. Modern technology enables, e.g., gate-to-gate time analysis (Supej and Holmberg, 2011), revealing the gate or turn at which the skier loses or gains time. This type of analysis has demonstrated that a skier can lose as much as 0.4 s on the first few gates of a course and, moreover, that when a skier loses time on flat terrain, he/she can regain gate-to-gate times comparable to those of the fastest skier only many gates later. Similarly, the time required for elite skiers to navigate special gate combinations, such as close to and after hairpin bends in slalom, varies considerably.

Nevertheless, evaluating performance on the basis of racing time alone, even on short sections of a course, involves several limitations (Supej, 2008). This time is influenced by the skier's initial velocity, position and orientation. Moreover, the position and orientation at the end of a section relative to the following gate, as well as the exit speed will exert little influence on section time, but may affect subsequent performance profoundly. Accordingly, other measures of performance are required.

[1]www.fis-ski.com

**TABLE 1 |** Characteristics of the alpine ski racing events at the Pyeongchang Olympic Games in 2018.

| Event | Course length (m) | | Vertical drop (m) | | Average gradient (°) | | Best run time (min:sec:hundredths) | | Number of gates (1st or 1st/2nd run) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | M | W | M | W | M | W | M | W | M | W |
| Slalom | 575 | 556 | 211 | 204 | 36.7 | 36.7 | 1:38:99 | 1:38:63 | 66/66 | 63/63 |
| Giant slalom | 1326 | 1250 | 440 | 400 | 33.2 | 32 | 2:18:04 | 2:20:02 | 53/53 | 51/51 |
| Super-G | 2322 | 2010 | 650 | 585 | 28 | 29.1 | 1:24:44 | 1:21:11 | 45 | 43 |
| Combined | | | | | | | | | | |
| Slalom | 521 | 515 | 200 | 179 | 38.4 | 34.8 | 45.96 | 40:23 | 60 | N/A |
| Downhill | 2050 | 2775 | 650 | 730 | 31.7 | 26.3 | 1:19.24 | 1:40:11 | 25 | 38 |
| Downhill | 2965 | 2775 | 825 | 730 | 27.8 | 26.3 | 1:40:25 | 1:39:22 | 33 | 38 |
| Team event | 265 | 265 | 80 | 80 | 30.2 | 30.2 | N/A | N/A | 26 | 26 |

*M, men; W, women; N/A, not available.*

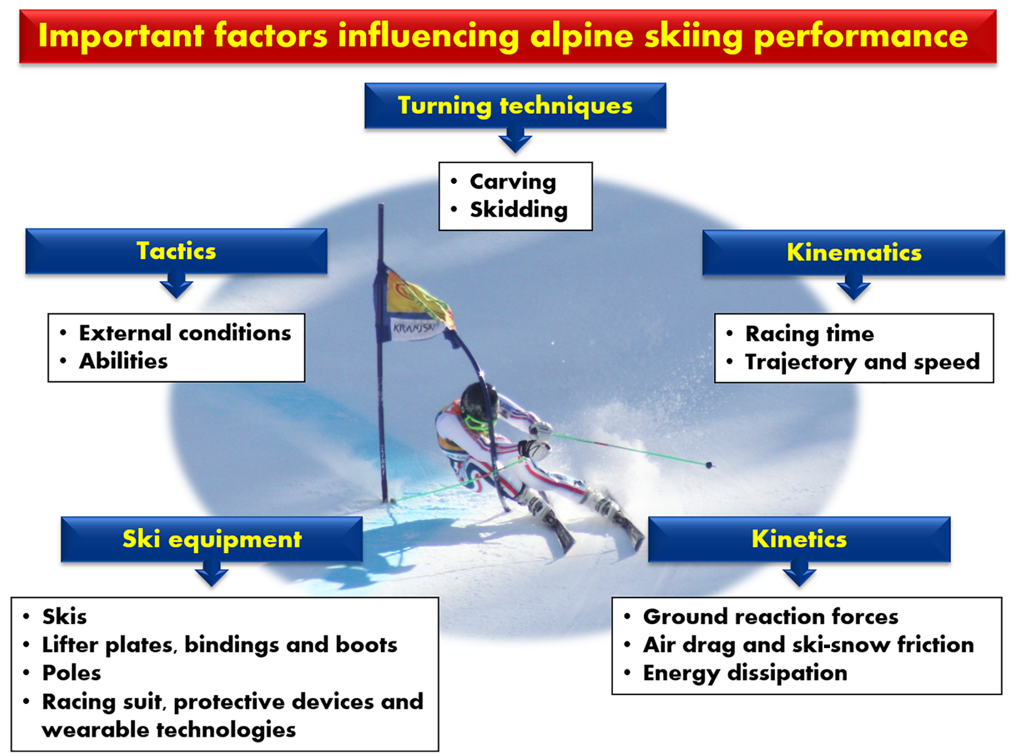


**FIGURE 1 |** Biomechanical determinants of the performance of Olympic alpine skiers.

## Trajectory and Speed

In general, skiing the shortest possible trajectory rapidly results in the fastest time (Supej, 2008; Federolf, 2012; Spörri et al., 2018). The ability to maintain high speed depends not only on the trajectory, but also on technique and tactics.

Usually, while often involving longer trajectories, faster and smoother turns are initiated higher up the slope and/or well before the gate, are completed closer to the gate and are longer (Brodie et al., 2008; Supej, 2008; Spörri et al., 2012b, 2018). Such turns generally allow greater acceleration out of/away from the gate and straighter subsequent skiing (Brodie et al., 2008), with faster entry into subsequent turns. Notably, instantaneous velocity is more influential than choice of trajectory or turning radius (i.e., the distance traveled) or, in other words, higher velocity is more advantageous than a shorter trajectory (Federolf, 2012).

# KINETICS

## Ground Reaction Forces

In alpine skiing, peak GRF, a common measure of the external load on the skier and equipment, can be as high as five times body weight in slalom (Supej et al., 2002). In the case of the other three major disciplines, the highest GRFs were observed during giant slalom, followed by super-G, with the lowest values during downhill racing (Gilgien et al., 2014). When turning, the GRFs are considerably higher during the steering than weight-transition phase, when they may even become zero if the skier loses ground contact (Supej et al., 2002, 2004; Reid, 2010; Vaverka et al., 2012; Falda-Buscaiot et al., 2017).

The distributions of GRFs for the best and less successful elite slalom skiers appear to be similar, although the most pronounced GRFs coincide with the lowest differential specific mechanical energy (i.e., highest energy dissipation/lower performance) (Supej et al., 2011). This is consistent with the observation that the shortest trajectory is not necessarily the fastest and may even be detrimental to the instantaneous performance of a skier, in particular during turns of short radius (Supej, 2008; Supej and Holmberg, 2010; Supej et al., 2011). Furthermore, slalom techniques involving both less zero GRF and lower maximal GRF are more efficient and faster (Supej et al., 2002; Hébert-Losier et al., 2014). These findings indicate that timing of GRFs may exert a pronounced impact on performance.

### Air Drag and Ski-Snow Friction

Aerodynamic drag and ski–snow friction are the only two mechanical forces that can have a detrimental impact on skiing performance (von Hertzen et al., 1997; Federolf et al., 2008; Meyer et al., 2012; Supej et al., 2013). Postures that minimize the exposed frontal area of a skier are key to reducing aerodynamic drag (Watanabe and Ohtsuki, 1977; Barelle et al., 2004), thereby elevating velocity (Watanabe and Ohtsuki, 1977) and reducing overall time (Watanabe and Ohtsuki, 1977; Luethi and Denoth, 1987). When skiing downhill, aerodynamic drag accounts for almost 50% of the differences in racing time between slower and faster skiers (Luethi and Denoth, 1987), whereas with giant slalom, this drag causes only 15% of the total energy loss per turn and is not considered a major determinant of performance (Supej et al., 2013). Aerodynamic drag becomes more important as the speed increases (e.g., from slalom to downhill) (Gilgien et al., 2013, 2018).

The opposite is true for ski-snow friction, which is more important at slower speeds, particularly when turning. During slalom and giant slalom races ski-snow friction dissipates most of the energy (Supej et al., 2013). Even in the speed disciplines, involving more intense turning, the skiers focus more on guiding the skis smoothly than minimizing the frontal area exposed.

### Energy Dissipation

Good turns are usually the result of effective usage of potential energy (i.e., minimization of ski-snow friction and aerodynamic drag in combination with optimizing ski trajectory). Such efficiency is particularly important in speed events and on the flat sections of most courses. However, in slalom and giant slalom, particularly on steeper slopes, minimization of energy dissipation does not necessarily ensure the shortest overall time. For elite skiers, minimization while maintaining high velocity and optimal trajectories on all sections also exerts a considerable impact on outcome.

Supej et al. (2008, 2011) reported that during a slalom event most energy is dissipated during steering in the vicinity of the gates and turns of short radius (< 15 m), and least during weight transition prior to initiation of a turn. In fact, during turns of short radius, the difference in specific mechanical energy is related directly to this radius (Supej et al., 2011), suggesting that longer turns may improve racing performance, as discussed above and consistent with the findings by Spörri et al. (2012b). Similarly, elite skiers optimize their use of potential energy more easily with carving than with skidding or pivoting turns (Supej, 2008).

To summarize, no individual biomechanical parameter can explain *why* one skier is faster than another (Hébert-Losier et al., 2014). Kinematic parameters reflect more the outcome of performance (i.e., without consideration of cause) and kinetic parameters the underlying causes. Elite skiers attempt to exploit these intricate interactions between biomechanical parameters and technique under varying conditions in a manner that minimizes descent times.

## SKI EQUIPMENT

### Skis

With respect to equipment, the continuous development of skis has influenced performance by elite alpine skiers most. For instance, when World Cup skiers first started to use "carving" skis in 1999, the smoother runs allowed faster skiing and shorter turns, particularly in slalom and giant slalom. In other disciplines, the length and side-cut radii increase with speed and turning radius (see **Table 2**). Moreover, enhanced awareness of injury and possible causes has led to regulation of the side-cut radii and waist width of skis by the FIS (**Table 2**) several times over the past decade (Burtscher et al., 2008; Spörri et al., 2012a, 2017; Haaland et al., 2016; Supej et al., 2017).

Racing skis have predominately a sandwich construction with a wooden core. Today's skis have a different overall geometry, contain more advanced materials and vary in camber curve. Thickness directly influences their longitudinal stiffness (Heinrich et al., 2011), which has been changing proportionally in response to side-cut radius regulations, particularly in GS. Improvements in construction and the servicing of metal edges of skis enable sharp and/or carving turns even on hard snow or ice (Brown, 2009). However, elite skiers have individual subjective preferences concerning longitudinal and torsional stiffness, as well as edge preparations.

### Lifter Plates, Bindings, and Boots

Lifter plates (between the ski and binding), introduced around the time of the Olympic Games in Calgary in 1988, allow more optimal bending. The associated increase in standing height allows more angling of the skis, in spite of regulation by the FIS (**Table 2**). Today's plates also improve the torsional stiffness of skis, dampen vibrations and enhance the release of ski bindings (Senner et al., 2013; Supej and Senner, 2017).

Ski boots have also undergone important development. Newer plastics and molding enable thinner, more anatomic outer shells.

**TABLE 2 |** International Ski Federation (FIS) regulations concerning the equipment and courses involved in international skiing competitions.

| Event | EQUIPMENT | | | | | | | COURSE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Minimal ski length (cm) | | Maximal ski waist width (cm) | Minimal side-cut radius (m) | | Standing height (with ski/plate/binding) (mm) | Boot height (from sole to top of foot bed) (mm) | Distance between gates (m) | Vertical drop (m) | | *Number of gates |
| | M | W | M/W | M | W | M/W | M/W | M/W | M | W | M/W |
| Slalom | 165 | 155 | 63** | No rule | No rule | 50 | 43 | 6–13*** | 180–220 | 140–220 | 30–35% |
| Giant slalom | 193 | 188 | 65 | 30 | 30 | 50 | 43 | 10–27 | 250–450 | 250–400 | 11–15% |
| Super-G | 210 | 205 | 65 | 45 | 40 | 50 | 43 | Minimally 25 | 400–650 | 400–600 | Minimally 35 |
| Downhill | 218 | 210 | 65 | 50 | 50 | 50 | 43 | No rule | 800–1100 | 450–800 | No rule |

*M, men, W, women. *The number of gates in Slalom and Giant Slalom is 30% of the vertical drop (e.g., 30% of 200 m means 60 gates), while in Super-G only the minimal number of gates is specified. **The maximal ski waist is regulated in all the events except slalom, where the minimal width is regulated instead. ***For special gate characteristics such as hairpins or delayed gates, the distances differ.*

In addition, boot-fittings have improved considerably, with individual liners and insoles, allowing better transfer of the skier's action to the skis. The viscoelastic properties of ski boots, with moment-angle hysteresis, still cause energy dissipation (Eberle et al., 2016; Knye et al., 2016). It is more important that flexural stiffness be lower for downhill than technical disciplines, enabling better gliding and lower tuck.

### Poles

In the speed disciplines (super-G and downhill), poles are utilized primarily for initial acceleration and balance; while in the technical disciplines, the pole plant also helps to rotate the body while initiating a turn (Müller et al., 1998), as well as to clear the gates in the case of slalom. Accordingly, speed skiers use longer poles that are shaped around their body for better tuck and less aerodynamic drag (Barelle et al., 2004; Meyer et al., 2012).

### Racing Suit, Protective Devices, and Wearable Technologies

Small differences in aerodynamic drag can exert a major impact on skiing speed and properly fitted suits with low permeability provide less drag. Therefore, individualized suits for each discipline are designed with the average speed in mind (Brownlie et al., 2010; Bardal and Reid, 2012). In alpine skiing helmets are used primarily for safety, but at the same time, they contribute substantially to aerodynamic drag, particularly in the tuck position (Thompson et al., 2001). In addition to helmets that protect the athlete's head from injury, the use of various other protective devices – i.e., protectors for the hand/arm, back, knee and lower-leg, knee orthoses and airbag systems – has been proposed in recent years (Spörri et al., 2017).

To optimize performance and/or ski equipment with respect to various biomechanical parameters (Supej et al., 2011; Hébert-Losier et al., 2014), skiers today are often equipped with wearable technologies, such as global navigation satellite systems (GNSS), inertial motion capture systems, accelerometers and sensors that measure GRF (Brodie et al., 2008; Krüger and Edelmann-Nusser, 2010; Supej, 2010; Vaverka and Vodickova, 2010; Supej and Holmberg, 2011; Nemec et al., 2014; Fasel et al., 2016; Falda-Buscaiot et al., 2017; Gilgien et al., 2018). Depending on the purpose and information required, different sensor technologies are used. When interference with the athlete must be minimized or there are other special needs/limitations, external devices such as photocells, radar guns and video recorders are employed (Krosshaug et al., 2007; Federolf et al., 2008; Supej and Holmberg, 2011; Supej et al., 2011, 2015; Federolf, 2012; Spörri et al., 2012b).

## TACTICAL ASPECTS OF OLYMPIC ALPINE SKIING

When skiers have mastered techniques, racing tactics become important, varying with ability and external conditions. In all disciplines, gate combinations, the course setup, and snow conditions influence tactical considerations. At the same time, the athletes must gain as much time as possible on sections that emphasize their strengths and minimize loss of time on sections that expose their weaknesses (Hébert-Losier et al., 2014).

Overall, the key to success appears to be more closely related to a skier's ability to maintain high-level performance, selecting the optimal turning technique and line of skiing, than achieving the fastest section time or highest instantaneous velocity (Hébert-Losier et al., 2014).

## FUTURE PERSPECTIVES

The margins between the times that result in gold and silver medals in Olympic alpine skiing are hundredths of a second (e.g., this difference in the case of the women's SG in Pyeongchang 2018 was 0.01 s), making all factors that influence performance extremely important. Although the biomechanics of alpine skiers have improved in recent decades, relatively little is yet known concerning optimization of performance over an entire course (Hébert-Losier et al., 2014) or interrelationships between skiing on successive sections (Supej and Cernigoj, 2006). Recent advances in GNSS technology allow precise biomechanical analysis of performance over an entire course in real-time (Supej et al., 2008, 2013; Supej, 2012; Gilgien et al., 2013), providing much more detailed information about such factors. In addition to measuring performance, inertial motion sensors and GNSS allow recording of 3D body kinematics over several turns or even an entire race course, providing accurate kinematic values on-snow (Brodie et al., 2008; Krüger and Edelmann-Nusser, 2010; Supej, 2010; Fasel et al., 2017). Continuous miniaturization of mechanical, electrical and optical sensing technologies for assessing the kinematics and kinetics of human motion and performance, as well as of other chemical sensing technologies designed to detect physiological parameters (not dealt with here) will allow more comfortable and flexible monitoring of technique, performance, tactics and training load (Heikenfeld et al., 2018). More user-friendly and automated software involving artificial intelligence (machine learning, neural networks and deep learning), in combination with wearable technology, is expected to allow real-time feedback in the near future (Nemec et al., 2014).

## CONCLUSION

In connection with future Olympic Games, regular and effective use of measurement technology and biomechanical feedback will improve and facilitate the work of coaches. Accordingly, both coaches and competitors will have to learn how to utilize novel technological possibilities for more efficient testing and selection of racing gear. The technical, physical and tactical strengths and weaknesses of an individual skier will become easier to identify. At the same time, the need to individualize training and skiing equipment will continue to motivate innovative scientific research for years to come.

## AUTHOR CONTRIBUTIONS

MS and H-CH contributed substantially to all parts of this paper, including the concept, designed, and wrote, and approved the final version for publication, as well as agreed to be accountable for all aspects of this work.

## FUNDING

The European Regional Development Fund No. 20201170 supported this study financially.

## REFERENCES


Bardal, L. M., and Reid, R. (2012). Testing of fabrics for use in alpine ski competition suits. *Procedia Eng.* 34, 44–49. doi: 10.1016/j.proeng.2012.04.009

Barelle, C., Ruby, A., and Tavernier, M. (2004). Experimental model of the aerodynamic drag coefficient in alpine skiing. *J. Appl. Biomech.* 20, 167–176. doi: 10.1123/jab.20.2.167

Brodie, M., Walmsley, A., and Page, W. (2008). Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing. *Sports Technol.* 1, 17–28. doi: 10.1080/19346182.2008.9648447

Brown, C. (2009). "Modeling edge–snow interactions using machining theory," in *Science and Skiing, IV*, eds S. L. E. Müller and T. Stöggl (Maidenhead: Meyer & Meyer Sport Ltd.), 175–182.

Brownlie, L., Larose, G., D'Auteuil, A., Allinger, T., Meinert, F., Kristofic, P., et al. (2010). Factors affecting the aerodynamic drag of alpine skiers. *Procedia Eng.* 2, 2375–2380. doi: 10.1016/j.proeng.2010.04.002

Burtscher, M., Gatterer, H., Flatz, M., Sommersacher, R., Woldrich, T., Ruedl, G., et al. (2008). Effects of modern ski equipment on the overall injury rate and the pattern of injury location in alpine skiing. *Clin. J. Sport Med.* 18, 355–357. doi: 10.1097/MJT.0b013e31815fd0fe

Chardonnens, J., Favre, J., Gremion, G., and Aminian, K. (2010). "A new method for unconstrained measurement of joint angle and timing in alpine skiing: Comparison of crossover and crossunder turns," in *proceedings of the 28 International Conference on Biomechanics in Sports*, eds R. Jensen, W. Ebben, E. Petushek, C. Richter, and K. Roemer (Milwaukee, WI: Marquette).

Eberle, R., Kaps, P., Heinrich, D., Mossner, M., Hofer, M., Schindelwig, K., et al. (2016). "A nonlinear moment-angle relation for the ski-boot hysteresis," in *Science and Skiing VI*, eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Maidenhead: Meyer & Meyer Sport), 143–150.

Erdmann, W. S., Giovanis, V., Aschenbrenner, P., Kiriakis, V., and Suchanowski, A. (2017). Methods for acquiring data on terrain geomorphology, course geometry and kinematics of competitors' runs in alpine skiing: a historical review. *Acta Bioeng. Biomech.* 19, 69–79.

Falda-Buscaiot, T., Hintzy, F., Rougier, P., Lacouture, P., and Coulmy, N. (2017). Influence of slope steepness, foot position and turn phase on plantar pressure distribution during giant slalom alpine ski racing. *PLoS One* 12:e0176975. doi: 10.1371/journal.pone.0176975

Fasel, B., Lechot, C., Spörri, J., Müller, E., and Aminian, K. (2016). "Body vibration and its transmission in alpine ski racing," in *Proceedings of the 14th International Symposium on 3D Analysis of Human Movement*, Taipei.

Fasel, B., Spörri, J., Schütz, P., Lorenzetti, S., and Aminian, K. (2017). An inertial sensor-based method for estimating the athlete's relative joint center positions and center of mass kinematics in alpine ski racing. *Front. Physiol.* 8:850. doi: 10.3389/fphys.2017.00850

Federolf, P., Scheiber, P., Rauscher, E., Schwameder, H., Lüthi, A., Rhyner, H. U., et al. (2008). Impact of skier actions on the gliding times in alpine skiing. *Scand. J. Med. Sci. Sports* 18, 790–797. doi: 10.1111/j.1600-0838.2007.00745.x

Federolf, P. A. (2012). Quantifying instantaneous performance in alpine ski racing. *J. Sports Sci.* 30, 1063–1068. doi: 10.1080/02640414.2012.690073

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015). Characterization of course and terrain and their effect on skier speed in world cup alpine ski racing. *PLoS One* 10:e0118119. doi: 10.1371/journal.pone.0118119

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gilgien, M., Spörri, J., Kröll, J., Crivelli, P., and Müller, E. (2014). Mechanics of turning and jumping and skier speed are associated with injury risk in men's world cup alpine skiing: a comparison between the competition disciplines. *Br. J. Sports Med.* 48, 742–747. doi: 10.1136/bjsports-2013-092994

Gilgien, M., Spörri, J., Kröll, J., and Müller, E. (2016). Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing. *Br. J. Sports Med.* 50, 8–13. doi: 10.1136/bjsports-2015-095465

Haaland, B., Steenstrup, S. E., Bere, T., Bahr, R., and Nordsletten, L. (2016). Injury rate and injury patterns in FIS world cup alpine skiing (2006-2015): have the new ski regulations made an impact? *Br. J. Sports Med.* 50, 32–36. doi: 10.1136/bjsports-2015-095467

Hébert-Losier, K., Supej, M., and Holmberg, H. C. (2014). Biomechanical factors influencing the performance of elite alpine ski racers. *Sports Med.* 44, 519–533. doi: 10.1007/s40279-013-0132-z

Heikenfeld, J., Jajack, A., Rogers, J., Gutruf, P., Tian, L., Pan, T., et al. (2018). Wearable sensors: modalities, challenges, and prospects. *Lab Chip* 18, 217–248. doi: 10.1039/c7lc00914c

Heinrich, D., Mössner, M., Kaps, P., and Nachbauer, W. (2011). A parameter optimization method to determine ski stiffness properties from ski deformation data. *J. Appl. Biomech.* 27, 81–86. doi: 10.1123/jab.27.1.81

Knye, M., Grill, T., and Senner, V. (2016). Flexural behavior of ski boots under realistic loads – The concept of an improved test method. *Procedia Eng.* 147, 342–347. doi: 10.1016/j.proeng.2016.06.305

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016a). Effect of ski geometry on aggressive ski behaviour and visual aesthetics: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 20–25. doi: 10.1136/bjsports-2015-095433

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016b). Sidecut radius and kinetic energy: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 26–31. doi: 10.1136/bjsports-2015-095463

Krosshaug, T., Slauterbeck, J. R., Engebretsen, L., and Bahr, R. (2007). Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scand. J. Med. Sci. Sports* 17, 508–519. doi: 10.1111/j.1600-0838.2006.00558.x

Krüger, A., and Edelmann-Nusser, J. (2010). Application of a full body inertial measurement system in alpine skiing: a comparison with an optical video based system. *J. Appl. Biomech.* 26, 516–521. doi: 10.1123/jab.26.4.516

Luethi, S. M., and Denoth, J. (1987). The influence of aerodynamic and anthropometric factors on speed in skiing. *Int. J. Sport Biomech.* 3, 345–352. doi: 10.1123/ijsb.3.4.345

Meyer, F., Le Pelley, D., and Borrani, F. (2012). Aerodynamic drag modeling of alpine skiers performing giant slalom turns. *Med. Sci. Sports Exerc.* 44, 1109–1115. doi: 10.1249/MSS.0b013e3182443315

Müller, E., Bartlett, R., Raschner, C., Schwameder, H., Benko-Bernwick, U., and Lindinger, S. (1998). Comparisons of the ski turn techniques of experienced and intermediate skiers. *J. Sport Sci.* 16, 545–559. doi: 10.1080/026404198366515

Müller, E., and Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J. Sports Sci.* 21, 679–692. doi: 10.1080/0264041031000140284

Nemec, B., Petric, T., Babic, J., and Supej, M. (2014). Estimation of alpine skier posture using machine learning techniques. *Sensors* 14, 18898–18914. doi: 10.3390/s141018898

Reid, R. (2010). *A Kinematic and Kinetic Study of Alpine Skiing Technique in Slalom. Doctoral Thesis*. Oslo: Norwegian School of Sport Sciences.

Senner, V., Michel, F. I., Lehner, S., and Brügger, O. (2013). Technical possibilities for optimising the ski-binding-boot functional unit to reduce knee injuries in recreational alpine skiing. *Sports Eng.* 16, 211–228. doi: 10.1007/s12283-013-0138-7

Spörri, J., Kröll, J., Amesberger, G., Blake, O. M., and Müller, E. (2012a). Perceived key injury risk factors in world cup alpine ski racing–an explorative qualitative study with expert stakeholders. *Br. J. Sports Med.* 46, 1059–1064. doi: 10.1136/bjsports-2012-091048

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012b). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach.* 7, 647–659. doi: 10.1260/1747-9541.7.4.647

Spörri, J., Kröll, J., Fasel, B., Aminian, K., and Müller, E. (2016a). Course setting as a prevention measure for overuse injuries of the back in alpine ski racing: a kinematic and kinetic study of giant slalom and slalom. *Orthop. J. Sports Med.* 4:2325967116630719. doi: 10.1177/2325967116630719

Spörri, J., Kröll, J., Gilgien, M., and Müller, E. (2016b). Sidecut radius and the mechanics of turning-equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 14–19. doi: 10.1136/bjsports-2015-095737

Spörri, J., Kroll, J., Gilgien, M., and Muller, E. (2017). How to prevent injuries in alpine ski racing: what do we know and where do we go from here? *Sports Med.* 47, 599–614. doi: 10.1007/s40279-016-0601-2

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2018). The role of path length- and speed-related factors for the enhancement of section performance in alpine giant slalom. *Eur. J. Sport Sci.* 18, 911–919. doi: 10.1080/17461391.2018.1453870

Supej, M. (2008). Differential specific mechanical energy as a quality parameter in racing alpine skiing. *J. Appl. Biomech.* 24, 121–129. doi: 10.1123/jab.24.2.121

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *J. Sports Sci.* 28, 759–769. doi: 10.1080/02640411003716934

Supej, M. (2012). "Gate-to-gate synchronized comparison of velocity retrieved from a high-end Global Navigation Satellite System in alpine skiing," in *Proceedings of the 28 International Conference on Biomechanics in Sports*, eds A. B. Elizabeth and J. Bradshaw (Melbourne: Patria A. Hume).

Supej, M., and Cernigoj, M. (2006). Relations between different technical and tactical approaches and overall time at men's world cup giant slalom races. *Kinesiologia Slovenica* 12, 63–69.

Supej, M., Hébert-Losier, K., and Holmberg, H. C. (2015). Impact of the steepness of the slope on the biomechanics of world cup slalom skiers. *Int. J. Sports Physiol. Perform.* 10, 361–368. doi: 10.1123/ijspp.2014-0200

Supej, M., and Holmberg, H. C. (2010). How gate setup and turn radii influence energy dissipation in slalom ski racing. *J. Appl. Biomech.* 26, 454–464. doi: 10.1123/jab.26.4.454

Supej, M., and Holmberg, H. C. (2011). A new time measurement method using a high-end global navigation satellite system to analyze alpine skiing. *Res. Q. Exerc. Sport* 82, 400–411. doi: 10.1080/02701367.2011.10599772

Supej, M., Kipp, R., and Holmberg, H. C. (2011). Mechanical parameters as predictors of performance in alpine world cup slalom racing. *Scand. J. Med. Sci. Sports* 21, e72–e81. doi: 10.1111/j.1600-0838.2010.01159.x

Supej, M., Kugovnik, O., and Nemec, B. (2002). New advances in racing slalom technique. *Kinesiologia Slovenica* 8, 25–29.

Supej, M., Kugovnik, O., and Nemec, B. (2004). Modelling and simulation of two competition slalom techniques. *Kinesiology* 36, 206–212.

Supej, M., Kugovnik, O., and Nemec, B. (2008). "DGPS measurement system in alpine skiing track and center of mass estimation," in *Proceedings of the First Joint International Pre-Olympic Conference of Sports Sciences and Sports Engineering. Computer Science in Sports*, eds Y. Jiang, A. Baca, and H. Zhang (Liverpool: World Academic Union), 120–125.

Supej, M., Nemec, B., and Kugovnik, O. (2005). Changing conditions on the slalom ski course affect competitors' performances. *Kinesiology* 37, 151–158.

Supej, M., and Senner, V. (2017). "Special design of ski plates may improve skiing safety," in *Snow Sports Trauma and Safety*, eds I. S. Scher, R. M. Greenwald, and N. Petrone (Cham: Springer International Publishing), 95–107.

Supej, M., Senner, V., Petrone, N., and Holmberg, H. C. (2017). Reducing the risks for traumatic and overuse injury among competitive alpine skiers. *Br. J. Sports Med.* 51, 1–2. doi: 10.1136/bjsports-2016-096502

Supej, M., Sætran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemec, B., et al. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand. J. Med. Sci. Sports* 23, e38–e47. doi: 10.1111/sms.12007

Thompson, B. E., Friess, W. A., and Knapp, K. N. (2001). Aerodynamics of speed skiers. *Sports Eng.* 4, 103–112. doi: 10.1046/j.1460-2687.2001.00072.x

Vaverka, F., and Vodickova, S. (2010). Laterality of the lower limbs and carving turn. *Biol. Sport* 27, 129–134. doi: 10.5604/20831862.913080

Vaverka, F., Vodickova, S., and Elfmark, M. (2012). Kinetic analysis of ski turns based on measured ground reaction forces. *J. Appl. Biomech.* 28, 41–47. doi: 10.1123/jab.28.1.41

von Hertzen, R., Holmlund, U., and Ranta, M. A. (1997). On the velocity maximization in downhill skiing. *J. Biomech.* 30, 525–529. doi: 10.1016/S0021-9290(96)00167-4

Watanabe, K., and Ohtsuki, T. (1977). Postural changes and aerodynamic forces in alpine skiing. *Ergonomics* 20, 121–131. doi: 10.1080/00140137708931611


**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 30 August 2018
doi: 10.3389/fphys.2018.01203

Check for updates

# A New Training Assessment Method for Alpine Ski Racing: Estimating Center of Mass Trajectory by Fusing Inertial Sensors With Periodically Available Position Anchor Points

*Benedikt Fasel[1], Matthias Gilgien[2,3], Jörg Spörri[4,5] and Kamiar Aminian[1]**

[1] Laboratory of Movement Analysis and Measurement, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, [2] Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway, [3] Center of Alpine Sports Biomechanics, St. Moritz Health and Innovation Foundation, St. Moritz, Switzerland, [4] Department of Sport Science and Kinesiology, University of Salzburg, Salzburg, Austria, [5] Department of Orthopaedics, Balgrist University Hospital, University of Zurich, Zurich, Switzerland

OPEN ACCESS

**Edited by:**
*Gianluca Vernillo,*
*Università degli Studi di Milano, Italy*

**Reviewed by:**
*Chiara Zoppirolli,*
*Università degli Studi di Verona, Italy*
*Yusuke Ishige,*
*Japan Institute of Sports Sciences (JISS), Japan*

***Correspondence:**
*Kamiar Aminian*
*kamiar.aminian@epfl.ch*

**Specialty section:**
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

**Received:** *23 April 2018*
**Accepted:** *10 August 2018*
**Published:** *30 August 2018*

**Citation:**
*Fasel B, Gilgien M, Spörri J and Aminian K (2018) A New Training Assessment Method for Alpine Ski Racing: Estimating Center of Mass Trajectory by Fusing Inertial Sensors With Periodically Available Position Anchor Points. Front. Physiol. 9:1203. doi: 10.3389/fphys.2018.01203*

In this study we present and validate a method to correct velocity and position drift for inertial sensor-based measurements in the context of alpine ski racing. Magnets were placed at each gate and their position determined using a land surveying method. The time point of gate crossings of the athlete were detected with a magnetometer attached to the athlete's lower back. A full body inertial sensor setup allowed to track the athlete's posture, and the magnet positions were used as anchor points to correct position and velocity drift from the integration of the acceleration. Center of mass (CoM) position errors (mean ± standard deviation) were 0.24 m ± 0.09 m and CoM velocity errors were 0.00 m/s ± 0.18 m/s. For extracted turn entrance and exit speeds the 95% limits of agreements (LoAs) were between −0.19 and 0.33 m/s. LoA for the total path length of a turn were between −0.06 and 0.16 m. The proposed setup and processing allowed estimating the CoM kinematics with similar errors than known for differential global navigation satellite systems (GNSS), even though the athlete's movement was measured with inertial and magnetic sensors only. Moreover, as the gate positions can also be obtained with non-GNSS based land surveying methods, CoM kinematics may be estimated in areas with reduced or no GNSS signal reception, such as in forests or indoors.

**Keywords: alpine ski racing, giant slalom, center of mass, kinematics, inertial sensors, sensor fusion, validation**

## INTRODUCTION

In the development of World class athletes' monitoring, assessment of their training quantity and quality and evaluation of their performance plays a substantial role also in snow sports. Among snow sports, alpine skiing sets high demands to measurement systems to assess training load and performance: the athlete's speed is high and they cover distances of several hundred meters or kilometers during competition and training in harsh outdoor conditions. Video and body worn sensor-based systems have been proposed to assess performance (Supej et al., 2005; Reid, 2010; Spörri et al., 2012) and training load (Spörri et al., 2015, 2017; Gilgien et al., 2018). To allow teams and athletes to use technology in the training assessment its user friendliness is a key aspect. The use of quantitative video-based analysis is extremely resource consuming and is therefore seldom applied, while the use of body worn sensor technology has increased substantially the last years, due to the efficiency of its application. While quantitative video-based analysis was proven having sufficient accuracy, body worn sensors need still further prove whether their accuracy is sufficient for its applications. To measure human body displacement in alpine ski racing using body worn sensors, differential global navigation satellite systems (GNSS) are recognized to be well suited. They allow obtaining the three dimensional (3D) antenna trajectory at a reasonably high sampling frequency with sub 5-cm accuracy for good GNSS conditions (Gilgien et al., 2014). For applications where overall body posture remains relatively constant, it can be assumed that the 3D center of mass (CoM) kinematics can be approximated by the GNSS antenna kinematics with sufficient precision (Terrier and Schutz, 2005; Townshend et al., 2008; Waldron et al., 2011; Scott et al., 2016). However, when body posture is changing significantly during motion cycles, and when instantaneous CoM kinematics are the variables of interest, an approximation of CoM by the kinematics of a GNSS antenna cannot be considered to be sufficiently valid. Thus, an alternative solution needs to be found to track the athlete's CoM 3D position relative to the GNSS antenna position.

The determination of the athlete's absolute 3D CoM position consists of two aspects: (1) the global GNSS antenna position in 3D and (2) the relative position of the CoM with respect to the GNSS antenna position in 3D. To this end, for alpine ski racing, two solutions were proposed: either a modeling approach (Supej et al., 2013; Nemec et al., 2014; Gilgien et al., 2015c) or, more commonly, a combination or fusion of GNSS with inertial sensors (Brodie et al., 2008; Supej, 2010; Fasel et al., 2016a). Generally, both solutions allow the estimation of absolute CoM trajectory with an accuracy and precision of <0.1 m, provided that differential GNSS is used. However, the use of differential GNSS has also two major drawbacks: (1) geodetic differential GNSS hardware and software are very costly and need to be handled by trained personnel and (2) good satellite coverage is needed, indeed signal shading by forest or topography is not unusual in competitive alpine ski racing. Thus, for routine measurements (e.g., during training sessions) this setup might have the disadvantage of being cumbersome and requires personnel trained in geodesy. Therefore, alternatives to measure CoM kinematics should be found.

As already mentioned, inertial sensors can be used to estimate the athlete's relative 3D CoM kinematics (i.e., relative CoM position with respect to a point on the athlete such as the head). For example, for indoor carpet skiing, an accuracy and precision of 0.03 and 0.01 m was found for the CoM position relative to the lumbar joint center (LJC) (Fasel et al., 2017c). The relative position of the athlete's head with respect to the LJC could be estimated with an accuracy and precision of 0.13 and 0.02 m, respectively (Fasel et al., 2017c). Considering the above-mentioned drawbacks, finding new solutions to estimate not only the relative but also the absolute CoM position would render the use of differential GNSS obsolete. However, the problem of inertial sensors is that they cannot measure the position directly. Instead, measured acceleration in the sensor frame has to be transformed into a global frame, Earth's gravity removed, and then integrated twice to finally obtain position. Eventual measurement errors from the first two steps may accumulate during the integration, resulting in large position drifts (i.e., the main limit of such methodology).

Biomechanical movement constraints can help to correct this drift. For example, in gait analysis where inertial sensors are fixed to the feet, drift can be reduced by setting speed to zero at each stance phase (Mariani et al., 2010). However, for activities without motionless periods, e.g., skiing where no stance-swing phases are present, this procedure cannot be applied. When combining inertial sensors and GNSS, 3D speed and position obtained with inertial sensors can be corrected periodically, each time a new GNSS reference sample is available (Grewal et al., 2013). However, such position reference samples (i.e., anchor points) may also come from a difference source, independent from a GNSS. If such anchor points are available at a sufficiently high rate, they could entirely replace the GNSS. If the athlete crosses *a priori* known locations and the corresponding times of crossing can be determined, these locations could be used as anchor points to correct the position drift from the integration of the acceleration. In alpine ski racing the athlete is constrained to follow a pre-defined path marked by gates. Therefore, these gates could be considered as potential anchor points. If the gate locations and the corresponding times of gate crossings are known, position drift could be corrected. Hence, it might be possible to measure an athlete's CoM trajectory by the sole use of inertial sensors (i.e., without any differential GNSS data being required). Gate locations could be measured using land surveying techniques (Gilgien et al., 2015a,b). Gate crossing times could be obtained by a magnetometer-based method as presented in Fasel et al. (2016c).

Accordingly, the aim of this study was to design and validate a system to estimate absolute 3D CoM kinematics during alpine giant slalom (GS) and downhill (DH) skiing without the use of GNSS (i.e., by the sole use of inertial sensor measurements fused with gate timing and gate position information as anchor points). In order to highlight the system's relevance for training, skiing performance related parameters derived from the CoM kinematics were tested for sensitivity to change.

## MATERIALS AND METHODS

### Experimental Setup

Seven inertial sensors (Physilog 4, Gait Up SA, Switzerland) recording acceleration and angular velocity at 500 Hz were fixed to the left and right shanks and thighs, to the sacrum, to the sternum, and to the helmet using medical tape (**Figure 1**). Additionally, the sacrum sensor contained a magnetometer sampling at 125 Hz. Accelerometer offset and sensitivity were corrected according to Ferraris et al. (1995). Gyroscope offset was corrected during a static moment before each run. Magnetometer offset, sensitivity and axis-misalignment were corrected according to Bonnet et al. (2009). A low-cost GNSS

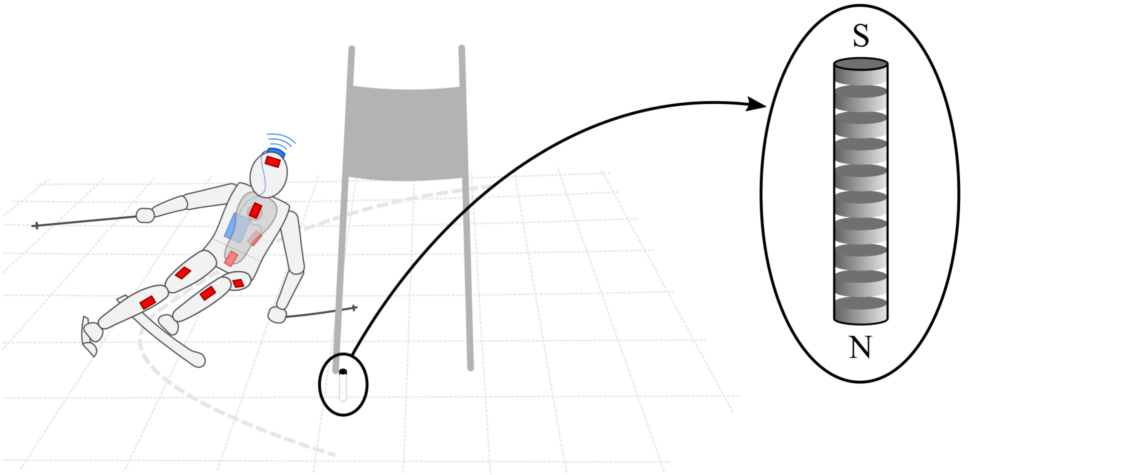


**FIGURE 1 |** Illustration of the experimental setup during a left turn. The inertial sensors are represented by the red boxes. The reference differential GNSS system is illustrated in blue with the antenna fixed to the helmet and the data logger worn on the back. The back protector contained the low-cost GNSS system with the antenna located approximately between the shoulder blades, as well as the data logger integrated in the inertial sensor fixed to the protector's left side. The magnets were completely buried into the snow, close to the gate's pole. A zoomed view of the buried magnet is provided on the right side of the illustration.

receiver (CAM-M8, u-blox, Switzerland) was placed in the athlete's back protector together with a GNSS antenna (TW2710, Tallysman, Canada) placed approximately at shoulder height. All inertial sensors and the GNSS receiver were wirelessly synchronized. Prior to each run, athletes performed functional calibration movements as described in Fasel et al. (2017d) to align the sensor frames to the anatomical frames of their respective segments. An additional static upright posture with slightly flexed knees and parallel skis was performed at the start and finish. Each gate of a GS course served as an anchor point and was equipped with a magnet. The magnet was constructed by vertically stacking 10 small neodymium magnets (S-20-10-N, Supermagnete, Switzerland) spaced by 5 mm to a 15 cm long stick (**Figure 1**). Magnet position at each gate was obtained using differential GNSS. Thus, each anchor point corresponds to a gate position, which was assumed to be identical to the magnet position.

## Measurement Protocol

Eleven European Cup level athletes performed a total of 17 runs on a typical 30-gates GS course with varying gate distances (21.8–27.8 m). Measurements were performed during four consecutive days. For each day a new course with similar specifications was set. The length of the course from start to finish was 700 m with a vertical drop of 150 m. Every day the position of each gate was geodetically surveyed using GNSS. All athletes gave written informed consent prior to the measurements and the study was approved by the Ethical committee of the École Polytechnique Fédérale de Lausanne (Study Number: HREC 006-2016).

## Simulation of DH Conditions

In DH, gate distances are roughly three times larger compared to GS (Gilgien et al., 2015a,b). Hence, distances between anchor points for the trajectory drift correction are larger and a decreased drift correction performance is expected. DH was simulated by considering only anchor points at every third GS gate for extended Kalman smoothers (EKS) fusion procedure.

## Inertial System Algorithm

### Data Processing Overview

After functional calibration, segment orientation was found with strap-down integration and joint orientation drift correction as described previously (Fasel et al., 2017d, 2018). To fuse the anchor points with acceleration data from the inertial sensor at the sacrum, two separate EKS (Hartikainen et al., 2011) were used. The first smoother was used to obtain an initial 3D sacrum trajectory based on the inertial data only (**Figure 2**). Since the sacrum sensor would not pass the anchor points (i.e., gates) with zero distance, the relative position offsets between each anchor point and sacrum sensor position at gate crossing had to be estimated (relative anchor point estimation). Next, the anchor points estimated with the inertial data were matched to the surveyed anchor points. Then, the second smoother fused the anchor points with the inertial data for obtaining a refined sacrum trajectory. Relative anchor points were re-estimated and matched again to the surveyed anchor points and the EKS was run a second time. Finally, the athlete's absolute CoM kinematics was determined by combining the sacrum's refined trajectory with the relative CoM position (**Figure 2**).

### Extended Kalman Smoother 1: Initial Sacrum Trajectory

The sacrum sensor's acceleration was expressed in the global frame ($X$-axis: forward with respect to the athlete's still posture at start; $Y$-axis: vertical, along Earth's gravity; $Z$-axis: cross-product between $X$- and $Y$-axis; and origin: sacrum position at start) and gravity was removed. To estimate the sacrum trajectory $p_{sacr}(t)$ an EKS with 15 states (3D position, 3D speed, 3D acceleration,

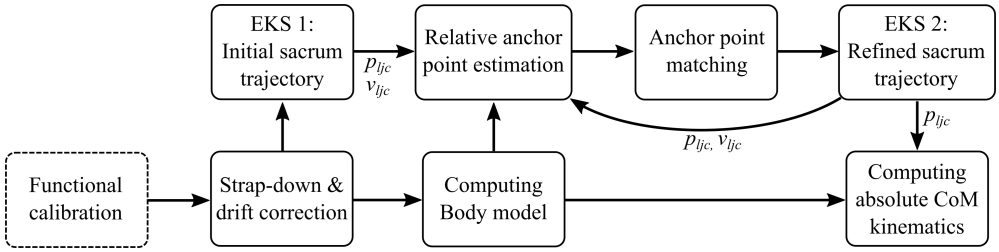


**FIGURE 2 |** Flow chart of the proposed algorithm for data processing. The outputs of the functional calibration were the rotation matrices that allow an alignment of each inertial sensor with the functional segment frames. The strap-down and drift correction provided the segment orientations in a common global frame. During the EKS 1 the initial sacrum (i.e., lumbar joint center, LJC) position and speed were obtained. Computing of the body model provided the athlete's joint and CoM positions relative to his LJC. The relative anchor point estimation provided the absolute gate positions in the inertial sensor frame and the relative gate positions at gate crossing with respect to the athlete's LJC. The anchor point matching computed the transformation between the estimated gate positions expressed in the inertial sensor frame and the global Earth reference frame and matches all estimated gate positions to the surveyed gate positions. The output of EKS 2 was a refined sacrum trajectory and speed. The output of the absolute CoM kinematics computation step was the final estimate of the position and speed of the CoM.

3D position offset, and 3 Euler angles representing residual orientation drift) integrated the gravity-corrected acceleration twice. A zero-velocity constraint during the static moments at start and finish was used to reduce the position drift. A constant-acceleration model was used for the state transitions.

## Body Model and Relative Anchor Point Estimation

The athlete's body model was obtained as described previously (Fasel et al., 2017c) with the LJC as the origin of the athlete's local coordinate system. Lower limb joint positions and athlete's CoM were estimated relative to the LJC. As for the sacrum's initial trajectory, azimuth was set to 0° at the static posture at start. Gate crossings were detected based on the peaks in the recorded magnetic field intensity at the sacrum sensor (Fasel et al., 2016c). For all further processing, it was assumed that the sacrum sensor position was at the same position as LJC [i.e., $p_{\text{sacr}}(t) = p_{\text{ljc}}(t)$ and in consequence $v_{\text{sacr}}(t) = v_{\text{ljc}}(t)$].

Suppose the skiing course consisted of $N$ gates equipped with magnets and $M$ gate crossings were detected [where $M$ may be different from $N$ due to missed gates (i.e., too wide distance from the magnet) or wrong detections due to signal noise]. The $N$ gates' magnet positions (i.e., anchor points) are denoted by $\{g_{\text{n}}\}$, $n \in [1; N]$. The $M$ "hypothetical" anchor points are denoted by $\{g_{\text{m}}\}$, $m \in [1; M]$. Suppose further that the LJC trajectory is denoted by $p_{\text{ljc}}(t)$ with $t$ being time, and that LJC speed is denoted by $v_{\text{ljc}}(t)$. For a given gate crossing $m$, detected at time $t_{\text{m}}$, the vector $r_{\text{m}}$ is relying $p_{\text{ljc}}(t_{\text{m}})$ to $g_{\text{m}}$ and $\hat{p}_{\text{m}}$ is the projection of $p_{\text{ljc}}(t_{\text{m}})$ onto the snow surface $S_{\text{m}}$ at gate $m$. $x_{\text{m}}$ is the vector connecting $\hat{p}_{\text{m}}$ to $g_{\text{m}}$ and is assumed to lie on $S_{\text{m}}$ and perpendicular to $v_{\text{ljc}}(t_{\text{m}})$ (**Figure 3**). $|r_{\text{m}}||$ can be estimated based on the magnetic field intensity at gate crossing, $||B(t_{\text{m}})||$. For a magnetic point source, its magnetic field intensity $||B||$ decays exponentially to the third power of the distance $||r||$ (Furlani, 2001). For the magnets used in this study, based on in-lab measurements with constant ambient magnetic field, the relation of $||B||$ to $||r||$ was approximated with Equation 1.

$$||r|| = \begin{cases} -0.4 * ||B|| + 1.0 & if\ ||B|| < 1.62 \\ -0.062 * ||B|| + 0.452 & else \end{cases} \quad (1)$$

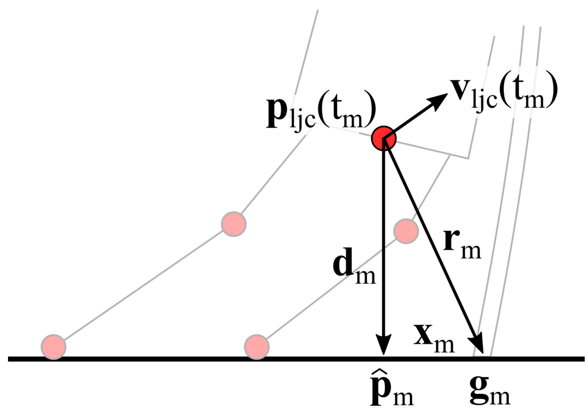


**FIGURE 3 |** Athlete posture relative to the gate seen from the back at gate crossing illustrated for a right turn. To simplify computation, it was assumed that the inertial sensor fixed to the sacrum would measure the acceleration, angular velocity, and magnetic field at the position of the LJC.

where the magnetometer was calibrated such that $||B|| = 1$ for $||r|| >> 0$.

However, $B(t_{\text{m}})$ did not allow a precise estimate of the xyz-components of $r_{\text{m}}$. Instead it was computed following Equations 2–4 for right turns and Equations 2–3 and 5 for left turns, using the trigonometric relations as illustrated in **Figure 3**. A turn was labeled as "right turn" if the sacrum's angular velocity along the trunk's longitudinal axis was negative at gate crossing.

$$r_{\text{m}} = d_{\text{m}} + x_{\text{m}} \quad (2)$$

$$d_{\text{m}} = \hat{p}_m - p_{\text{lcj}}(t_{\text{m}}) \quad (3)$$

$$x_{\text{m}} = \sqrt{||r_{\text{m}}||^2 - ||d_{\text{m}}||^2} * \frac{d_{\text{m}} \times v_{\text{m}}}{||d_{\text{m}} \times v_{\text{m}}||} \quad (4)$$

$$x_{\text{m}} = \sqrt{||r_{\text{m}}||^2 - ||d_{\text{m}}||^2} * \frac{v_{\text{m}} \times d_{\text{m}}}{||v_{\text{m}} \times d_{\text{m}}||} \quad (5)$$

To estimate $S_{\text{m}}$, first, snow contact points of the left and right feet were obtained by combining $p_{\text{ljc}}(t)$ with the athlete's body model.

It was supposed that the contact point of each leg was located 0.15 m distally from its ankle joint center, along the shank's longitudinal axis. Second, the average ski line $l(t)$ was computed by averaging between the left and right contact points. Finally, $S_m$ was obtained by fitting a plane to $l(t),\ t \in [t_m - 0.4sec;\ \ t_m + 0.4\,sec]$. Thus, $\hat{p}_m$ could be computed according to Equation 6.

$$\hat{p}_m = p_{ljc}(t_m) + \left(\left(\bar{l}_m - p_{ljc}(t_m)\right) \cdot n_m\right) * n_m \tag{6}$$

where $\bar{l}_m$ is a random point on $S_m$ (e.g., average of $l(t),\ t \in [t_m - 0.4sec;\ \ t_m + 0.4\,sec]$), $n_m$ the normal vector of $S_m$, and $\cdot$ the dot product.

### Anchor Point Matching

The matching of $\{g_n\},\ n \in [1; N]$ with $\{g_m\},\ m \in [1; M]$ was conducted under the hypothesis that not all N anchor points may have been detected and that additional anchor points may have been wrongly found due to noise in the recorded magnetic field. Since $\{g_m\}$ are expressed in the inertial sensor's global frame $J$ where both the position and azimuth were initialized to zero during the static posture performed at start, the transformation from $J$ to the global Earth reference frame $\mathcal{G}$ had to be found first. Note that the vertical axes of $J$ and $\mathcal{G}$ were already aligned and that only an azimuth rotation angle $\alpha$ and translation $o$ had to be found. To this end, both $\{g_n\}$ and $\{g_m\}$ where interpreted as point clouds. The azimuth rotation angle was defined as the angle between the first principal components of $\{g_n\}$ and $\{g_m\}$ projected onto the horizontal plane. To find $o$, $\{g_n\}$ needed to be matched to $\{\hat{g}_m\}$, the azimuth aligned point cloud of $\{g_m\}$. To find the best matching solution, a feature vector $f_n$ and $f_m$ was constructed for each point in $\{g_n\}$ and $\{\hat{g}_m\}$, respectively. To construct the features, each anchor point was described relative to its preceding and following anchor point. In addition, each turn was labeled as left/right based on the measured angular velocity and was assigned a turn number (Equations 7–8). To assign turn numbers it was assumed that the first detected anchor point was turn number one and that no two consecutive left or right turns could occur. For each point in $\{\hat{g}_m\}$, the closest matching point $k_m$ in $\{g_n\}$ was then found by the minimization of Equation 9. Matchings were removed if two or more points of $\{\hat{g}_m\}$ were matched to the same point in $\{g_n\}$. $o$ was then defined as the median position difference of all matched pairs.

$$f_n = [g_{n+1} - g_n,\quad g_n - g_{n-1},\quad [l/r],\quad n]^T \tag{7}$$

$$f_m = [\hat{g}_{m+1} - \hat{g}_m,\ \hat{g}_m - \hat{g}_{m-1},\ [l/r],\ m]^T \tag{8}$$

$$k_m = \underset{n \in [1;N]}{\arg\min} \|f_n - f_m\| \tag{9}$$

Subsequently, $\{g_m\}$ was corrected for azimuth and position offset and expressed in frame $\mathcal{G}$. Denote these points as $\{^{\mathcal{G}}g_m\}$. To find the final matching between the estimated anchor points $\{^{\mathcal{G}}g_m\}$ and the surveyed anchor points $\{g_n\}$ the same minimization as described above was used a second time. However, since offset was corrected, feature vectors finally consisted of the absolute position, the left/right turn, and the turn number (Equations 10, 11).

$$f_n = [g_n,\quad [l/r],\quad n]^T \tag{10}$$

$$f_m = [^{\mathcal{G}}g_m,\quad [l/r],\quad m]^T \tag{11}$$

### Extended Kalman Smoother 2: Refined Sacrum Trajectory

As expected, the sacrum trajectory $p_{ljc}(t)$ which was solely obtained by integration of the sacrum acceleration and by zero-velocity drift correction was not very accurate and position drifts of up to 20 m were observed. Therefore, an accurate estimation of $\{g_m\}$ could not be guaranteed and not all matching pairs $k_m$ were identifiable. Thus, after a first passage through the EKS, the estimation of $\{g_m\}$ and the anchor point matching were performed a second time. But this time it was based on the updated sacrum trajectory. Finally, the EKS was run a second time to obtain an improved estimation of the sacrum's trajectory. To account for the improved accuracy of $\{g_m\}$ the position accuracy of $\{g_m\}$ in the EKS was reduced from 1 m for the first iteration to 0.1 m for the second iteration.

### Absolute CoM Kinematics Estimation

Finally, the absolute CoM trajectory $p_{CoM,\,inertial}(t)$ was obtained by adding the relative CoM position obtained from the body model to the refined sacrum trajectory (Fasel et al., 2016a, 2017c). The athlete's CoM speed $v_{CoM,\,inertial}(t)$ was obtained by the three-point derivation of $p_{CoM,\,inertial}(t)$. Both $p_{CoM,\,inertial}(t)$ and $v_{CoM,\,inertial}(t)$ were low-pass filtered with a 2$^{nd}$ order Butterworth filter with cut-off frequency of 5 Hz.

## GNSS Reference System

The reference system consisted of a differential geodetic GNSS with the GNSS antenna (G5Ant-2AMNS1, Antcom, Canada) fixed to the athlete's helmet. The receiver (Alpha-G3T, Javad, United States) was placed in a backpack and logged GPS and GLONASS signals using the L1 and L2 frequencies. A reference base station (receiver: Alpha-G3T, Javad, United States; antenna: GrAnt, Javad, United States) was placed at the end of the ski course. 3D antenna positions were sampled at 50 Hz and obtained in post processing as described in (Gilgien et al., 2013, 2015c). Ambiguities were fixed for the entire run for all runs. Synchronization with the inertial sensor-based system was performed with the GPS timestamp. To obtain antenna trajectory at 500 Hz the antenna position samples were fused with the head's inertial sensor data using an EKS with twelve states (3D position, 3D speed, 3D acceleration, and 3D acceleration offsets). This trajectory was then combined with the athlete's body model derived from the inertial sensors described and validated in (Fasel et al., 2016a, 2017c) to obtain the reference 3D CoM trajectory $p_{CoM,ref}(t)$. 3D CoM speed $v_{CoM,ref}(t)$ was obtained by three-point derivation of $p_{CoM,ref}(t)$. In the end, both $p_{CoM,ref}(t)$ and $v_{CoM,ref}(t)$ were low-pass filtered with a 2nd order Butterworth filter with cut-off frequency of 5 Hz.

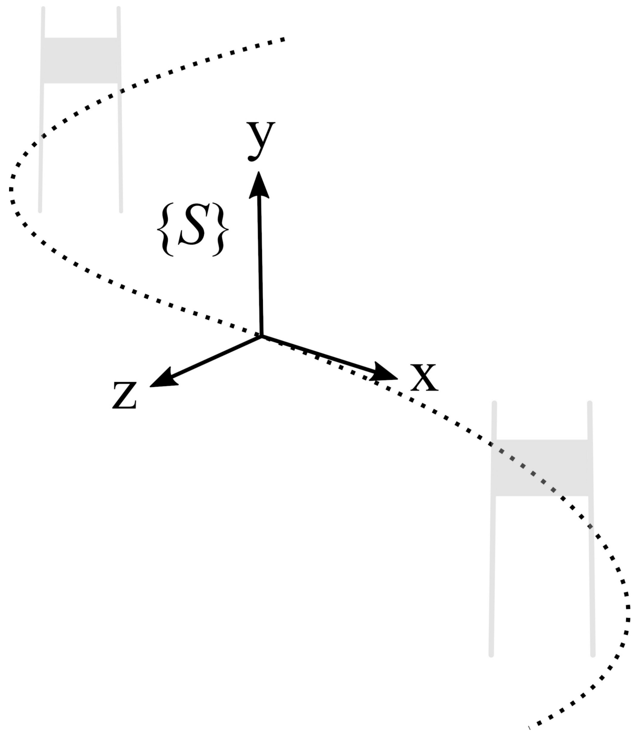


**FIGURE 4 |** Definition of the local skiing frame coordinates. The *x*-axis is parallel to the CoM velocity vector, the *z*-axis is the cross-product of the *x*-axis and the gravity (i.e., vertical axis), and the y-axis is the cross product of the *z*- and *x*-axes. The dotted line indicates the trajectory of the athlete's CoM.

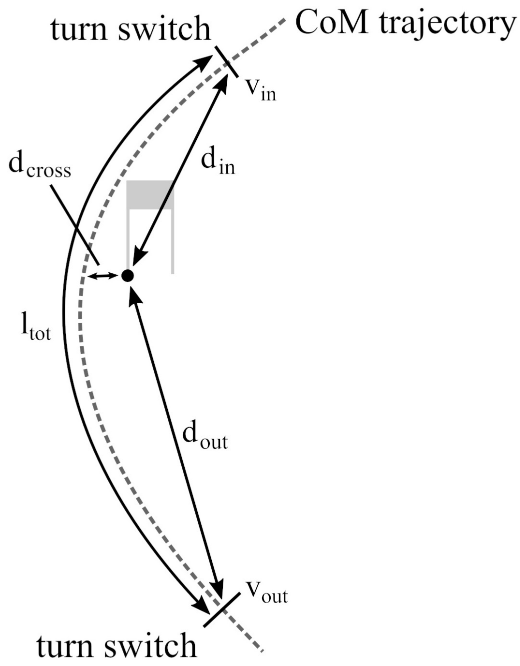


**FIGURE 5 |** Illustration of a turn's distance and speed performance parameters. A turn starts and stops at a turn switch and speed and position at these moments as well as at gate grossing are then expressed in relation to the gate position.

## Validation

### CoM Kinematics

For each run the 3D trajectory error $d(t)$ was obtained with $d(t) = p_{\mathrm{CoM,\,inertial}}(t) - p_{\mathrm{CoM,ref}}(t)$. The norm of the trajectory difference, i.e., $d_{\mathrm{tot}}(t) = ||d(t)||$, was used to evaluate the error with respect to the reference system. To allow a better error description, $d(t)$ was also expressed in the local skiing frame $\mathcal{S}$ [${}^{\mathcal{S}}d(t)$] which was defined as follows: the $x$-axis was pointing along the reference CoM velocity vector, the $z$-axis was the cross-product of the $x$-axis and the gravity vector, and the $y$-axis was the cross product of the $z$- and $x$-axes (**Figure 4**). Next, per run-accuracy and precision were calculated with the average and standard deviation of $d_{\mathrm{tot}}(t)$ and ${}^{\mathcal{S}}d(t)$, respectively. Overall accuracy was then defined as the average of all per-run accuracies and overall precision was defined as the average of all per-run precisions. The total speed error $S_{\mathrm{tot}}(t)$ was defined as the difference of the speed norms: $S_{\mathrm{tot}}(t) = ||v_{\mathrm{CoM,inertial}}(t)|| - ||v_{\mathrm{CoM,ref}}(t)||$. ${}^{\mathcal{S}}S(t)$ was obtained the same way as ${}^{\mathcal{S}}d(t)$.

### Performance Parameters Derived From CoM Kinematics

In order to validate whether the proposed system was sensitive enough to detect changes in performance, for one representative turn, five performance parameters were computed with both the reference and the inertial sensor-based system and for all runs. In analogy to a previous study by (Spörri et al., 2012) the performance parameters compared were: $d_{\mathrm{in}}$ distance from turn switch marking the beginning of the turn to the gate position, $d_{\mathrm{out}}$ distance from turn switch marking the end of the turn to the gate position (**Figure 5**). For these two events the instantaneous CoM speed norm ($v_{\mathrm{in}}$, $v_{\mathrm{out}}$) were extracted. For the same turn, total 3D CoM trajectory length $l_{\mathrm{tot}}$ was computed. In addition, the CoM distance to the gate at gate crossing ($d_{\mathrm{cross}}$) was extracted to evaluate the relative anchor point estimation. The beginning of a turn (i.e., turn switch) was detected based on the criterion of equal left/right ankle distance to the athlete's CoM (Fasel et al., 2016b). The parameter results were then compared based on Bland–Altman plots and LoAs were computed (Bland and Altman, 1999).

# RESULTS

## CoM Kinematics

The trajectory's overall accuracy and precision were 0.24 and 0.09 m for position, and 0.00 and 0.18 m/s for speed (**Table 1**). Errors were similar along each axis in the local skiing frame *S*. On average, one to two gates per run could not be detected by the magnetometers because the athlete passed too far from a gate; usually the first and/or last gate were not detected. It was observed that the magnetic field created by the magnets could always be detected up to a distance of approximately 0.80 m. Increasing the distance between available anchor points for trajectory drift correction decreased the accuracy and precision (**Table 1**).

**TABLE 1 |** Average (standard deviation) accuracy and precision for the total error and the error along each local skiing axis for speed and position.

| | | All gates | | Simulated DH | |
|---|---|---|---|---|---|
| | | **Accuracy** | **Precision** | **Accuracy** | **Precision** |
| **Speed, m/s** | Total error | 0.00 (0.02) | 0.18 (0.02) | 0.01 (0.03) | 0.31 (0.14) |
| | *X*-Axis | −0.01 (0.01) | 0.30 (0.04) | 0.00 (0.01) | 0.33 (0.05) |
| | *Y*-Axis | 0.00 (0.01) | 0.20 (0.03) | −0.01 (0.03) | 0.33 (0.14) |
| | *Z*-Axis | 0.00 (0.00) | 0.21 (0.08) | 0.00 (0.01) | 0.22 (0.08) |
| **Position, m** | Total error | 0.24 (0.09) | 0.09 (0.03) | 0.34 (0.10) | 0.19 (0.14) |
| | *X*-Axis | 0.01 (0.10) | 0.14 (0.03) | 0.00 (0.12) | 0.18 (0.04) |
| | *Y*-Axis | 0.02 (0.13) | 0.10 (0.02) | 0.03 (0.13) | 0.25 (0.18) |
| | *Z*-Axis | 0.01 (0.10) | 0.07 (0.04) | 0.01 (0.11) | 0.08 (0.04) |

*All values were obtained with the inertial sensor-based system only with surveyed anchor points. For the simulated downhill (DH) only every third anchor point was used for the fusion.*

**TABLE 2 |** Average parameter values and error mean with LoA for the extracted performance parameters.

| | Parameter value | | Error | | |
|---|---|---|---|---|---|
| | **Average** | **Std** | **Lower LoA** | **Mean** | **Upper LoA** |
| $v_{in}$, m/s | 19.94 | 1.04 | −0.18 | 0.08 | 0.33 |
| $v_{out}$, m/s | 20.30 | 0.82 | −0.19 | −0.01 | 0.17 |
| $d_{in}$, m | 12.59 | 1.29 | −0.27 | 0.02 | 0.32 |
| $d_{out}$, m | 13.41 | 1.56 | −0.25 | 0.02 | 0.30 |
| $d_{cross}$, m | 0.70 | 0.10 | −0.27 | 0.01 | 0.28 |
| $l_{tot}$, m | 26.35 | 1.38 | −0.06 | 0.05 | 0.16 |

## Performance Parameter-Related Findings

Limits of agreement were between −0.27 and 0.32 m for position, between −0.19 and 0.33 m/s for speed, and −0.06 and 0.16 m for path length (**Table 2**). With the exception of gate distance at gate crossing, LoAs were up to five times smaller than the performance parameter's standard deviation (**Table 2**). Gate distance error seemed to depend on the distance: small gate distances were overestimated and large gate distances were underestimated (**Figure 6**).

# DISCUSSION

In this study, alpine ski racing gates were equipped with magnets, and their positions were fused with magnetic and inertial sensor measurements to obtain drift-free absolute 3D CoM kinematics (trajectory and speed) of the skier. Gate and magnet positions (i.e., anchor points) were determined using surveying technology. Considering that the sacrum would not pass the anchor points with zero distance, the position difference between the athlete's sacrum and anchor points was estimated based on the athlete's posture and the peak magnitude of the magnetic field. Absolute CoM kinematics were obtained by adding the estimated CoM relative to the LJC to the estimated absolute LJC trajectory. The measurement performances of the system to estimate CoM trajectory and speed as well as ski performance parameters were estimated against a differential GNSS as reference with 17 runs on a GS course and a simulated DH.

## Accuracy and Precision of CoM Kinematics

We found good accuracy and precision for both CoM position (0.24 and 0.09 m) and speed (0.00 and 0.18 m/s) for GS (**Table 1**). In the context of alpine ski racing, no other study proposed to compute 3D CoM kinematics based on inertial sensors and surveyed anchor points. (Brodie et al., 2008) used a low-cost global positioning system (GPS) sampling at 1 Hz and fused position and speed data with acceleration obtained from inertial sensors. In addition, the start and finish points were used as anchor points for removing position offsets of the GPS. Nevertheless, over a 300 m run errors of up to ±1.5 m were reported. For differential GNSS (Gilgien et al., 2014) reported antenna position error standard deviations of <0.05 m. Using the same system but for CoM trajectories, (Gilgien et al., 2015c) reported error standard deviations of 0.12 m for position and 0.19 m/s for speed. Thus, even though the proposed system did not use differential GNSS the observed errors were comparable to the above systems.

When removing anchor points to simulate a DH race, position accuracy and precision decreased from 0.24 and 0.09 m to 0.34 and 0.19 m, respectively, as expected (**Table 1**). Instead of a position update in the EKS filter approximately every 1.5 s, such an update could only be performed approximately every 4.5 s. Interestingly, errors in the horizontal plane increased more than

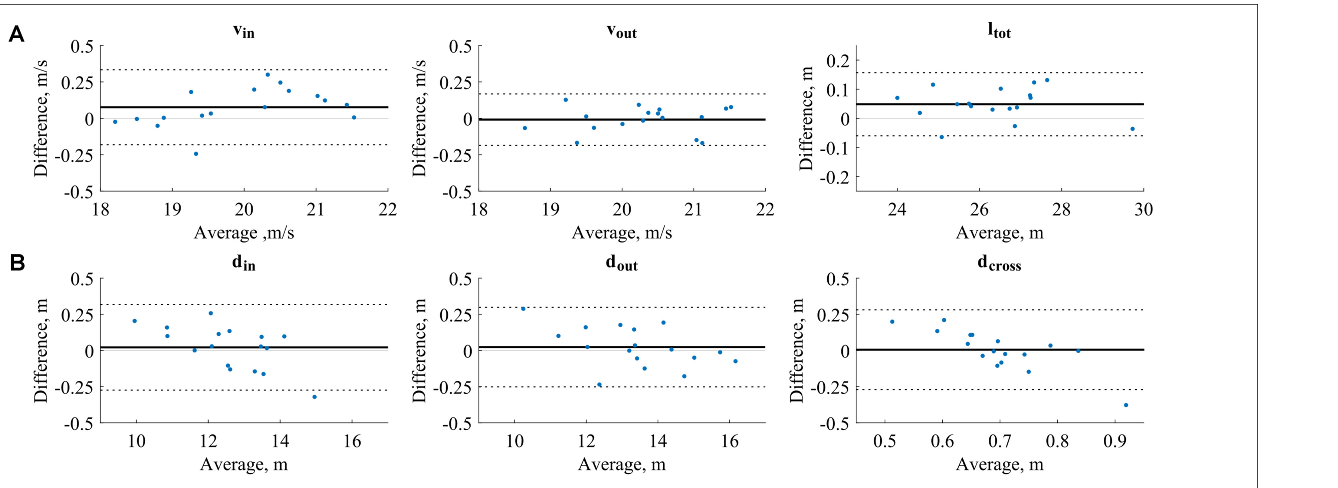


**FIGURE 6 |** Bland-Altman plots for the performance parameter validation. The solid black lines mark the mean error and the dashed black lines the limits of agreements.

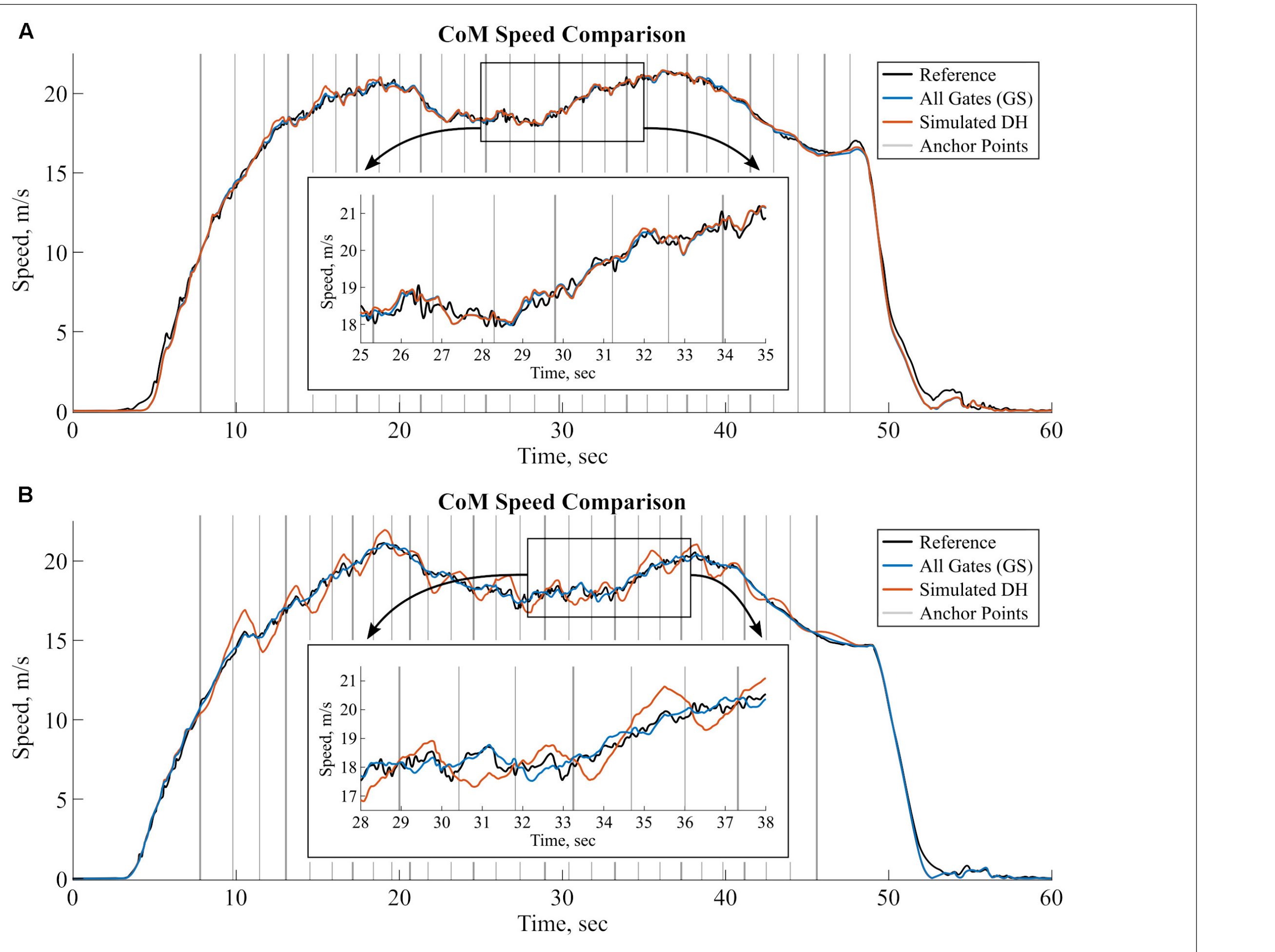


**FIGURE 7 |** CoM Speed comparison for two typical runs with different error behavior for the simulated DH. In both plots, reference CoM speed is shown in black, inertial sensor-based CoM speed with all anchor points (GS) is shown in blue, and the simulated DH is shown in red. Anchor points are marked with the vertical gray lines. For GS all anchor points were considered whereas for simulated DH only the anchor points marked in bold were considered. **(A)** A run with little to no change of speed between GS and simulated DH. **(B)** Another run with large precision decrease for simulated DH compared to GS.

along the vertical axis (**Table 1**). This could most likely be due to the law of the cosine for the removal of the gravity on the vertical axis and the horizontal plane. Since $1 - \cos(\varepsilon) << \sin(\varepsilon)$, for a small inclination error ε due to drift, the partly erroneous gravity removal has only little effect on the vertical axis compared to the horizontal plane. Thus, much less error could accumulate along the vertical axis compared to the horizontal plane.

We could also observe two different error behaviors when switching from GS to simulated DH: for part of the measurements the precision did not decrease much (**Figure 7A** shows an example run) while for the other part of the measurements the precision did decrease much more (**Figure 7B**). Depending on the turn direction, the CoM speed for simulated DH was either over- or under-estimated and was close to the reference value at each gate crossing, even at the ones were no anchor point was available. This suggests that for some of the runs, a movement-dependent speed bias was present that the EKS was not able to completely remove. One cause could be an insufficient modeling of the EKS which was designed and optimized for one turn between each anchor point whereas the simulated DH had three turns between each anchor point. For our simulated DH condition, a different design of the EKS should maybe be used to correct these errors. Nevertheless, for real DH with one turn between each anchor point, we expect that the proposed EKS would lead to a better precision than found with the simulated EKS in this study. A new study with real DH conditions should be performed in order to confirm the results of the simulated DH.

## Limits of Agreement for CoM-Derived Performance Parameters

Spörri et al. (2012) observed turn entrance and exit speed and distance differences of at least 0.3 m/s and 0.3 m, respectively, for comparisons between the fastest and slowest runs of the same athlete in GS. The LoA found in this study are of the same magnitude (**Table 2**). However, for total turn COM trajectory length, LoA were below the reported difference of 0.3 m between the fastest and slowest trial reported in (Spörri et al., 2012) for GS. Therefore, the system's resolution might be at the limit for detecting instantaneous performance-related differences such as speed and position at a certain point but may be well suited for "averaged" performance-related differences such as trajectory lengths in GS. To assess speed differences between athletes (Gilgien et al., 2016a) or speed differences caused by different types of skis in the same athlete (Gilgien et al., 2016b) in DH, the conclusion with respect to accuracy of the proposed system is similar as for GS. Differences between single runs might be hard to detect due to the fact, that the accuracy for speed of the proposed system is about equal to the differences expected between athletes or ski interventions.

## Limitations

A first limitation of the study was the constraint that the athletes had to pass each anchor point sufficiently close so that the perturbation in the Earth magnetic field caused by the buried magnet could be detected reliably. The magnets used in this study allowed detecting gate crossings up to distances of approximately 0.80 m. For the technical disciplines of slalom and GS and elite athletes this is no problem: they pass most of the gates as close as possible. Therefore, their sacrum passes the gate rarely with a distance larger than this limiting distance. However, with lower level athletes and in the speed disciplines super-G and DH gates may be passed with larger distances. This could be counter-acted by increasing the strength of the magnets or by placing several magnets along a line perpendicular to the expected ski trajectories and, in consequence, an adapted EKS.

A second limitation of the study was that the gates still had to be surveyed using a differential GNSS or a tachymeter. Thus, even though the athletes do not need to wear an expensive and sometimes difficult to handle differential GNSS, such a system was still needed for the gate surveying. For certain applications where relative position and speed information is sufficient, it might be possible to average anchor point positions computed from all runs on the same track (Fasel et al., 2017a) and leave out the surveying work. Another possibility would be to use a similar approach but including a low-cost GNSS worn by the athletes (Fasel et al., 2017b).

Despite the fact that the fusion of anchor points with inertial sensors allowed correcting speed and position drift, such performance would probably not have been possible without a considerable pre-processing effort. The sensors' offsets and sensitivities were carefully calibrated prior to the measurements. Moreover, sensor orientation drift was reduced prior to the EKS with the joint drift reduction procedure (Fasel et al., 2017d, 2018). This allowed estimating sensor orientations with dedicated, non-linear and precise methods, instead of directly including orientation estimation and drift reduction by means of a general model in the EKS. Thus, the EKS could be kept as simple as possible (i.e., with a minimum number of states and only few filter parameters needed to be tuned). The employed EKS was considered as *a means to an end* instead of forming the core of the study. The filter parameters were only chosen empirically and more work should be spent on properly tuning these parameters in a future study. The system's performance could also be improved by a better estimation of the relative position of the anchor points with respect to the sacrum. The estimation of the total distance between the sacrum and the anchor point (i.e., magnet) based on the measured magnetic peak intensity could involve some errors: it was highly probable that the magnetic peak field intensity was underestimated because of the magnetometer's low sampling rate of 125 Hz. At 20 m/s (i.e., 72 km/h) the athlete covers 0.16 m per sample. Therefore, it is likely that the magnetic intensity was not sampled exactly at its peak. Peak intensity could be measured more reliably by increasing the sampling rate and designing an advanced curve fitting and peak identification algorithm. Moreover, the magnetic field intensity created by the magnet decreases with the third power of the distance. Therefore, small measurement errors for low intensities can lead to large errors for the distance estimation. Stronger magnets would increase the generated magnetic field and lead to a more reliable distance estimation. At the same time, fewer gates would be missed since the magnetic disturbance could also be measured for gate distances larger than 0.80 m.

## CONCLUSION

The proposed system that fuses inertial sensors with periodically available anchor point positions allowed obtaining CoM kinematics with a higher accuracy and precision than with a system solely based on a low-cost GNSS (Brodie et al., 2008; Gilgien et al., 2014). Moreover, the proposed system's performance was close to that of geodetic differential GNSS (i.e., reference system). The independency of the proposed system from the use of GNSS allows its application also in indoor situations, such as in skiing halls.

## AUTHOR CONTRIBUTIONS

BF, MG, and JS conducted the data collection. BF, MG, JS, and KA conceptualized the study design, contributed to the analysis and interpretation of the data. BF drafted the manuscript, all other authors revised it critically. All authors approved the final version and agreed to be accountable for all aspects of this work.

## FUNDING

The study was funded by the Swiss Federal Office of Sport (FOSPO), grant 15-01; VM10052 and was partly supported by the "Fondation de soutien à la recherche dans le domaine de l'orthopédie et traumatologie".

## ACKNOWLEDGMENTS

The authors would like to thank Swiss-Ski and the participating athletes. This paper is based on Fasel (2017), where the initial algorithms were adapted and the text was shortened.

## REFERENCES

Bland, J. M., and Altman, D. G. (1999). Measuring agreement in method comparison studies. *Stat. Methods Med. Res.* 8, 135–160. doi: 10.1177/096228029900800204

Bonnet, S., Bassompierre, C., Godin, C., Lesecq, S., and Barraud, A. (2009). Calibration methods for inertial and magnetic sensors. *Sens. Actuators A Phys.* 156, 302–311. doi: 10.1016/j.sna.2009.10.008

Brodie, M., Walmsley, A., and Page, W. (2008). Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing. *Sports Technol.* 1, 17–28. doi: 10.1002/jst.6

Fasel, B. (2017). *Drift Reduction for Inertial Sensor Based Orientation and Position Estimation in the Presence of High Dynamic Variability During Competitive Skiing and Daily-Life Walking.* Ph.D. thesis, Lausanne, Switzerland: EPFL. doi: 10.5075/epfl-thesis-7803

Fasel, B., Gilgien, M., Spörri, J., and Aminian, K. (2017a). "Estimation of the centre of mass kinematics in alpine ski racing using inertial and magnetic sensors," in *Proceedings of the 35th Conference of the International Society of Biomechanics in Sports (ISBS)*, Cologne.

Fasel, B., Spörri, J., Gilgien, M., and Aminian, K. (2017b). "The fusion of magneto-inertial sensors with low-cost GNSS can improve the accuracy of determining centre of mass kinematics in alpine ski racing," in *Proceedings of the 9th Annual Congress of the Swiss Society of Sports Sciences (SGS)*, Zurich.

Fasel, B., Spörri, J., Schütz, P., Lorenzetti, S., and Aminian, K. (2017c). An inertial sensor-based method for estimating the athlete's relative joint center positions and center of mass kinematics in alpine ski racing. *Front. Physiol.* 8:850. doi: 10.3389/fphys.2017.00850

Fasel, B., Spörri, J., Schütz, P., Lorenzetti, S., and Aminian, K. (2017d). Validation of functional calibration and strap-down joint drift correction for computing 3D joint angles of knee, hip, and trunk in alpine skiing. *PLoS One* 12:e0181446. doi: 10.1371/journal.pone.0181446

Fasel, B., Sporri, J., Chardonnens, J., Kroll, J., Muller, E., and Aminian, K. (2018). Joint inertial sensor orientation drift reduction for highly dynamic movements. *IEEE J. Biomed. Health Inform.* 22, 77–86. doi: 10.1109/JBHI.2017.2659758

Fasel, B., Spörri, J., Gilgien, M., Boffi, G., Chardonnens, J., Müller, E., et al. (2016a). Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors. *Remote Sens.* 8:671. doi: 10.3390/rs8080671

Fasel, B., Spörri, J., Gilgien, M., Gerber, N., Falbriard, M., Müller, E., et al. (2016b). "IMU and GNSS-based turn switch detection in alpine ski racing," in *Proceedings of the 7th International Congress on Science and Skiing*, St. Christoph am Arlberg.

Fasel, B., Spörri, J., Kröll, J., and Aminian, K. (2016c). "Alpine ski racing gate crossing detection using magnetometers," in *Proceedings of the 7th International Congress on Science and Skiing*, Salzburg.

Ferraris, F., Grimaldi, U., and Parvis, M. (1995). Procedure for effortless in-field calibration of three-axis rate gyros and accelerometers. *Sens. Mater.* 7, 311–330.

Furlani, E. P. (2001). *Permanent Magnet and Electromechanical Devices: Materials, Analysis, and Applications*. Cambridge, MA: Academic Press.

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015a). Characterization of course and terrain and their effect on skier speed in world cup alpine ski racing. *PLoS One* 10:e0118119. doi: 10.1371/journal.pone.0118119

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015b). Correction: characterization of course and terrain and their effect on skier speed in world cup alpine ski racing. *PLoS One* 10:e0128899. doi: 10.1371/journal.pone.0128899

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., Limpach, P., and Müller, E. (2015c). Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *J. Sports Sci.* 33, 960–969. doi: 10.1080/02640414.2014.977934

Gilgien, M., Haugen, P., and Reid, R. (2016a). "A new instantaneous performance parameter for alpine skiing and individual sports," in *Proceedings of the 21st Annual Congress of the European College of Sport Science*, Vienna, 234–235.

Gilgien, M., Spörri, J., Kröll, J., and Müller, E. (2016b). Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing. *Br. J. Sports Med.* 50, 8–13. doi: 10.1136/bjsports-2015-095465

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gilgien, M., Spörri, J., Limpach, P., Geiger, A., and Müller, E. (2014). The effect of different Global Navigation Satellite System methods on positioning accuracy in elite alpine skiing. *Sensors* 14, 18433–18453. doi: 10.3390/s141018433

Grewal, M. S., Andrews, A. P., and Bartone, C. G. (2013). *Global Navigation Satellite Systems, Inertial Navigation, and Integration*, 3rd Edn. Hoboken, NJ: John Wiley & Sons.

Hartikainen, J., Solin, A., and Särkkä, S. (2011). *Optimal filtering with Kalman filters and smoothers – a Manual for Matlab toolbox EKF / UKF version 1.3*. Espoo: University School of Science.

Mariani, B., Hoskovec, C., Rochat, S., Büla, C., Penders, J., and Aminian, K. (2010). 3D gait assessment in young and elderly subjects using foot-worn inertial sensors. *J. Biomech.* 43, 2999–3006. doi: 10.1016/j.jbiomech.2010.07.003

Nemec, B., Petrič, T., Babič, J., and Supej, M. (2014). Estimation of alpine skier posture using machine learning techniques. *Sensors* 14, 18898–18914. doi: 10.3390/s141018898

Reid, R. C. (2010). *A Kinematic and Kinetic Study of Alpine Skiing Technique in Slalom*. Ph.D. thesis, Norvegian school of sport science, Oslo.

Scott, M. T. U., Scott, T. J., and Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport. *J. Strength Cond. Res.* 30, 1470–1490. doi: 10.1519/JSC.0000000000001221

Spörri, J., Kröll, J., Fasel, B., Aminian, K., and Müller, E. (2017). The use of body worn sensors for detecting the vibrations acting on the lower back in alpine ski racing. *Front. Physiol.* 8:522. doi: 10.3389/fphys.2017.00522

Spörri, J., Kröll, J., Haid, C., Fasel, B., and Müller, E. (2015). Potential mechanisms leading to overuse injuries of the back in alpine ski racing: a descriptive biomechanical study. *Am. J. Sports Med.* 43, 2042–2048. doi: 10.1177/0363546515588178

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach.* 7, 647–660. doi: 10.1260/1747-9541.7.4.647

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *J. Sports Sci.* 28, 759–769. doi: 10.1080/02640411003716934

Supej, M., Nemec, B., and Kugovnik, O. (2005). Changing conditions on the slalom ski course affect competitors' performances. *Kinesiology* 37, 151–158.

Supej, M., Saetran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemec, B., et al. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand. J. Med. Sci. Sports* 23, e38–e47. doi: 10.1111/sms.12007

Terrier, P., and Schutz, Y. (2005). How useful is satellite positioning system (GPS) to track gait parameters? A review. *J. Neuroeng. Rehabil.* 2:28. doi: 10.1186/1743-0003-2-28

Townshend, A. D., Worringham, C. J., and Stewart, I. B. (2008). Assessment of speed and position during human locomotion using nondifferential GPS. *Med. Sci. Sports Exerc.* 40, 124–132. doi: 10.1249/mss.0b013e3181590bc2

Waldron, M., Worsfold, P., Twist, C., and Lamb, K. (2011). Concurrent validity and test–retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *J. Sports Sci.* 29, 1613–1619. doi: 10.1080/02640414.2011.608703

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 13 November 2018
doi: 10.3389/fphys.2018.01541

# Estimating Alpine Skiers' Energetics and Turn Radius Using Different Morphological Points

***Frédéric Meyer* and Fabio Borrani***

*Institute of Sport Science, University of Lausanne, Lausanne, Switzerland*

Alpine ski analysis has always been very challenging, mainly due to the environmental conditions, large field and rapid and dynamic skiers' movements. Global navigation satellite system (*GNSS*) offers a solution adapted to outdoor testing, but the relationship between the point where the antenna is attached and the real centre of mass (*CoM*) position is still unknown. This article proposes to compare different points of the body used to quantify the performance of alpine skiers. 3D models of seven elite skiers performing giant slalom (*GS*) were built using multiple camera system and dedicated motion tracking software. *CoM* as well as pelvis, head and feet trajectories were deduced from the data. The potential and kinetic energies corresponding to these points were calculated, as well as the evolution of the turn radius during the turn cycle. Differences between values given by the *CoM* and the other morphological points were analyzed. The pelvis offered the best estimation of the *CoM*: No differences were found for the biomechanical parameters, except for the kinetic energy, where 2% of the turn cycle had significant different values. The head was less accurate compared to the pelvis, showing significant differences with *CoM* between 7 and 20% of the turn cycle depending on the parameter. Finally, the feet offered the worst results, with significant differences between 16 and 41% of the turn cycle. Energies and turn radius calculated by using pelvis in place of *CoM* offered similar patterns, allowing the analysis of mechanical and dissipation energy in *GS*. This may potentially enable easier testing methods to be proposed and tested.

**Keywords: centre of mass, potential energy, kinetic energy, GNSS, giant slalom**

OPEN ACCESS

***Edited by:***
*Gianluca Vernillo, Università degli Studi di Milano, Italy*

***Reviewed by:***
*Thomas Leonhard Stöggl, University of Salzburg, Austria*
*Ted Polglaze, University of Western Australia, Australia*

****Correspondence:***
*Frédéric Meyer*
*frederic.meyer@unil.ch*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *30 May 2018*
***Accepted:*** *15 October 2018*
***Published:*** *13 November 2018*

***Citation:***
*Meyer F and Borrani F (2018) Estimating Alpine Skiers' Energetics and Turn Radius Using Different Morphological Points. Front. Physiol. 9:1541. doi: 10.3389/fphys.2018.01541*

## INTRODUCTION

Human movement analyses are usually based on the body centre of mass *(CoM)* position determination. Mechanics of different sports have widely been studied, showing the necessity to calculate the *CoM* with a good accuracy to perform precise analysis [e.g., walking (Cavagna et al., 1963; Saibene and Minetti, 2003; Willems et al., 1995), running (Kyröläinen et al., 2001), cycling (Chèze et al., 1995)]. However, *CoM* calculations usually require large infrastructures such as 3D camera system (Richards, 1999) or a force platform (Barbier et al., 2003). Kinematic arms (Belli et al., 1993) and global navigation satellite system (*GNSS*) (Terrier et al., 2005) have also been used in running and walking analysis, but these methods use a point situated on the back of the subject to approximate the *CoM*. Slawinski et al. (2004) analyzed the use of a lumbar point for the estimation of potential and kinetic mechanical power in running. With this method, they found an overestimation of the kinetic power and underestimation of the potential power. Nevertheless, results obtained by using either a fixed point on the back or the *CoM* were well correlated. Gard et al. (2004) compared three methods (i.e., force platform, marker on the sacrum and full body model) to determine vertical displacement of the *CoM* during walking. They highlighted an overestimation of the vertical displacement of the *CoM* with the sacrum marker. In alpine skiing, the *CoM* has also been used as a reference to perform technical analysis (Kagawa, 2001; Schiefermüller et al., 2005), trajectories and speed analysis (Lešnik and Zvan, 2003) and to analyze energy balance of skiers performing turns both in giant slalom (*GS*) (Supej et al., 2005; Supej, 2008) and in slalom (Reid et al.2009). More recently, Fasel et al. (2016) used both *GNSS* and inertial sensors to determine *CoM* in alpine skiing. An accuracy and precision of 0.08 and 0.04 m respectively were reported for the *CoM* position.

Multiple camera systems are commonly used to reconstruct 3D models of the athlete, and *CoM* is then calculated, with de Leva adjustments (De Leva, 1996), using mathematical models of the body based on Hanavan (1964), Clauser et al. (1969), or Zatsiorsky (1983). However, this method only enables the recording of a small acquisition volume (usually one or two gates) and suffers from the approximation induced by the model. Alternatively, the use of low cost, high accuracy *GNSS* have expanded, allowing analyzing trajectories during a whole run (Waegli and Skaloud, 2007; Gomez-Lopez et al., 2009; Waegli and Skaloud, 2009; Waegli et al., 2009). However, since the *CoM* is not a fixed body point, the link between the antenna trajectory and the real *CoM* of the skier need to be determined. Gilgien et al. (2013) used the pendulum principle to estimate the distance between the real *CoM* position and the position given by a *GNSS* antenna placed on the helmet. Another solution could be to place the antenna to different positions. Therefore, the aim of this work was to compare the use of either the *CoM* or other morphological points to determine delta of potential energy *(ΔEpot)*, kinetic energy *(Ekin)* and turn radius *(Trad)* of alpine skiers performing *GS*.

# MATERIALS AND METHODS

## Participants

Seven European Cup and FIS racers [mean ± standard deviation *(SD):* body mass 98.8 ± 9.1 kg; height 1.82 ± 0.07 m; *GS* FIS points 26.45 ± 14.58] participated in the study. All participants were healthy males without any joint motion problems (World Medical Association, 2013).

## Experimental Design and Setting

A *GS* run was set up with a total of six gates, with a linear gate distance of 24 m and a lateral offset of 9 m. The first three gates were used to initiate the rhythm, and the next three were recorded. The slope angle was approximately 22 degrees. Six panning and tilting cameras, 1004*1004 pixels resolution, 48 Hz (PiA1000, Basler, Switzerland) were positioned around the *GS* run, about 35 m from the center of the zone of acquisition (i.e., video captured). Each camera was mounted on a special tripod head, especially built to always keep the sensor center of the camera at the same 3D coordinate, even when the camera was rotated to track the skier. Reference markers mounted on poles were positioned around the run to act as calibration and reference points for the panning and tilting reconstruction. The capture volume was around 60 * 20 * 2 m (**Figure 1A**). The positions of each reference marker, gate and camera were measured with a reflectorless total station *(theodolite + laser range finder, LQTS-522D, Longqiang, China*). The cameras' 3D coordinates were calculated as the median of two points on either side of the tilting axis of the camera. Each camera was connected with Gigabit Ethernet to a dedicated laptop which directly recorded the frames in the RAM memory of the computer, using a software developed for this specific purpose *(Swistrack, Thomas Lochmatter, Switzerland)*. Cameras were also connected to battery packs and dedicated synchronization boxes (Meyer et al., 2012). These boxes use *GNSS* signal to achieve wireless synchronization of the cameras recording system and ensure images from the six cameras are taken simultaneously with an error of less than 2.00 μs.

The athletes used their own *GS* skis to completed three trials of the *GS*. The runs were recorded and the time needed to go through three considered gates was estimated by counting the number of images captured on video. The fastest run of each skier was then analyzed (typical speed around 20 m/s). The selected runs were processed with SIMI motion software *(SIMI motion, SIMI, Germany),* using the panning and tilting modules. The camera's internal (e.g., focal length, image format and principal point) and external (e.g., camera position and orientation) parameters needed for the analysis were determined using the DLT 11 calibration method (Hatze, 1988; Abdel-Aziz and Karara, 2015).

Participants had to wear a white racing suit previously equipped with 14 black markers, a black helmet, and black gloves. *CoM* of both ski poles were also marked with black markers. In total, 19 markers were identified, and 3D models composed of 14 segments were built (**Figure 1B**). The *CoM* of the skier was calculated using the model proposed by Clauser et al. (1969) modified to take the material's weight into account. Tree morphological points that could be used for further analysis (e.g., *GNSS* antenna placement) were also defined: The *Pelvis* position was defined as the middle point between the 2 trochanters' markers, the *Feet* position as the middle point between the 2 ankle-bone markers and the *Head* position as the center of the helmet.

The accuracy of the reconstruction method was measured in two different ways. First, the positions of three gates as given by the total station were compared with the positions calculated by the software. Second, the error in the length of each body segment was determined.

## Parameters Analysis

The Δ*Epot* (J/kg), *Ekin* (J/kg), and *Trad* (1/m), were calculated for the *CoM* and the three morphological points *(i, with*

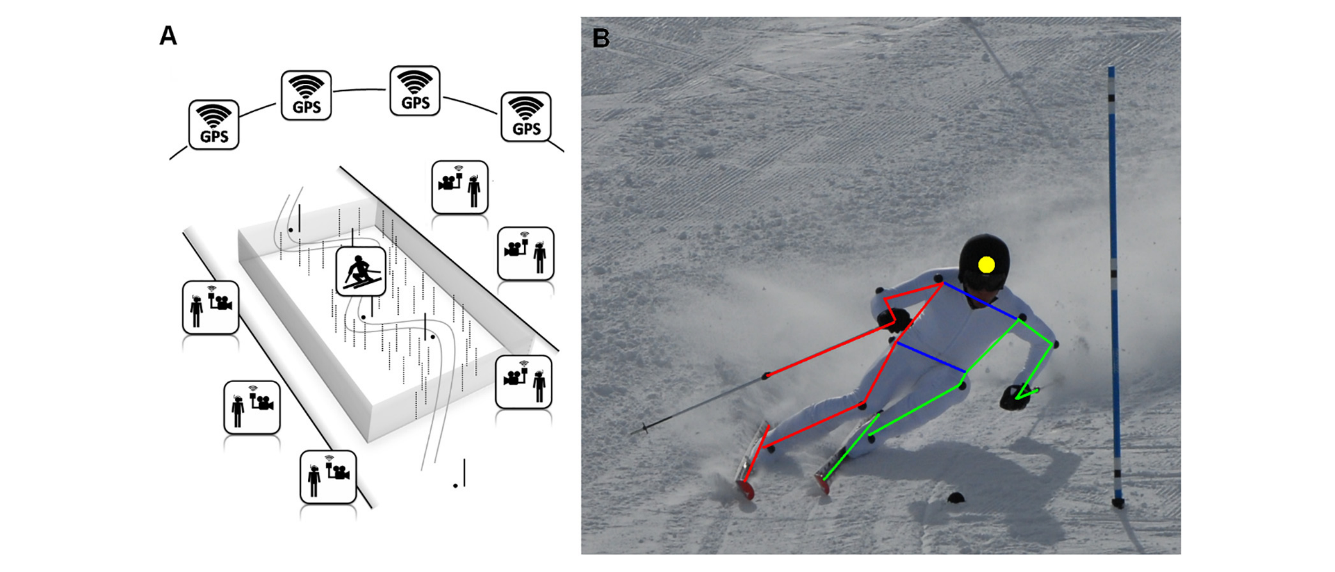


**FIGURE 1 | (A)** Slope setup showing the cameras, the gates and the reference points positions, **(B)** skier suit, markers and body segments.

*i = {CoM, Head, Pelvis, Feet})*. For analysis purposes, each trial was normalized to fit a 100% temporal turn cycle, where 0 and 100% were the time points when the projection of the *CoM* was between the two skis. A cubic B-splines interpolation method was used to achieve the normalization (Greville, 1964; Lee et al., 1997).

### Potential Energy

As the different morphological points are positioned at different heights of the body, the $\Delta Epot_i$ was calculated at each percent of the turn cycle, using the mass of the skier including equipment *(M)*, the acceleration due to gravity *(g)* and the delta height $(\Delta H_i(t))$ of the analyzed point in a global reference system:

$$\Delta Epot_i(t) = M \cdot g \cdot \Delta H_i(t) \tag{1}$$

### Kinetic Energy

The $Ekin_i$ evolution during the turn was calculated using the speed $(V_i)$ of the analyzed points (calculated as the time derivative of the point coordinate) and *M*, using the following equation:

$$Ekin_i(t) = 0.5 \cdot M \cdot V_i(t)^2 \tag{2}$$

The mean *Ekin* $(Ekin_m)$ was also calculated over the whole turn cycle, to show the overall error when using a morphological point instead of the *CoM*.

### Turn Radius

The $Trad_i$ were calculated directly with SIMI motion, using the Frenet-Serret formula (Serret, 1851; Frenet, 1852). The turn entry $(Tentry_i)$ was defined as the instant where the $Trad_i$ dropped below the natural radius of the skis (i.e., 25 m) and the turn exit $(Texit_i)$ as the instant where the turn radius went over 25 m again.

### Statistical Analysis

Statistical parametric mapping (*SPM*) was used on paired Student *T*-Tests (Pataky, 2010; Pataky et al., 2015) to analyze data over the whole turn cycle, to compare $\Delta Epot$, *Ekin* and *Trad* obtained for the morphological points to the *CoM* reference. The fit between the curves was assessed by summing percent of time of a turn cycle where *SPM* indicate significant differences (*tt* values with $p < .05$). Paired Student *T*-tests were also used to assess statistical differences between the *CoM* and the morphological points for the $Ekin_m$, *Tentry*, and *Texit,* given as mean ± *SD*. For all statistical analyses, significance was accepted at $p < .05$.

## RESULTS

### 3D Accuracy

For the global gates position reconstruction using the 3D reconstruction software, a horizontal mean error of 14.0 ± 8.0 mm was calculated, giving a 95% limit of agreement of 27.1 mm. For the vertical error, the absolute mean of 5.9 ± 3.5 mm gave a 95% limit of agreement of 11.6 mm. Adding the horizontal and the vertical errors led to a total 3D reconstruction error of 15.7 ± 7.8 mm, and a 95% limit of agreement of 28.3 mm. The segments lengths mean error of 13.0 ± 12.0 mm led to a 95% limit of agreement of 32.7 mm.

### Potential Energy

Using the *Head* instead of the *CoM* to estimate $\Delta Epot$ led to significantly different values for 12% of the time course of the turn during the turn cycle. The corresponding curves are plotted on **Figure 2A** with the corresponding *SPM* results on **Figure 2B** (*tt* threshold at ±5.90).

When the *Pelvis* was used instead of the *CoM* to calculate $\Delta Epot$, no significantly different values were obtained. **Figure 2C**

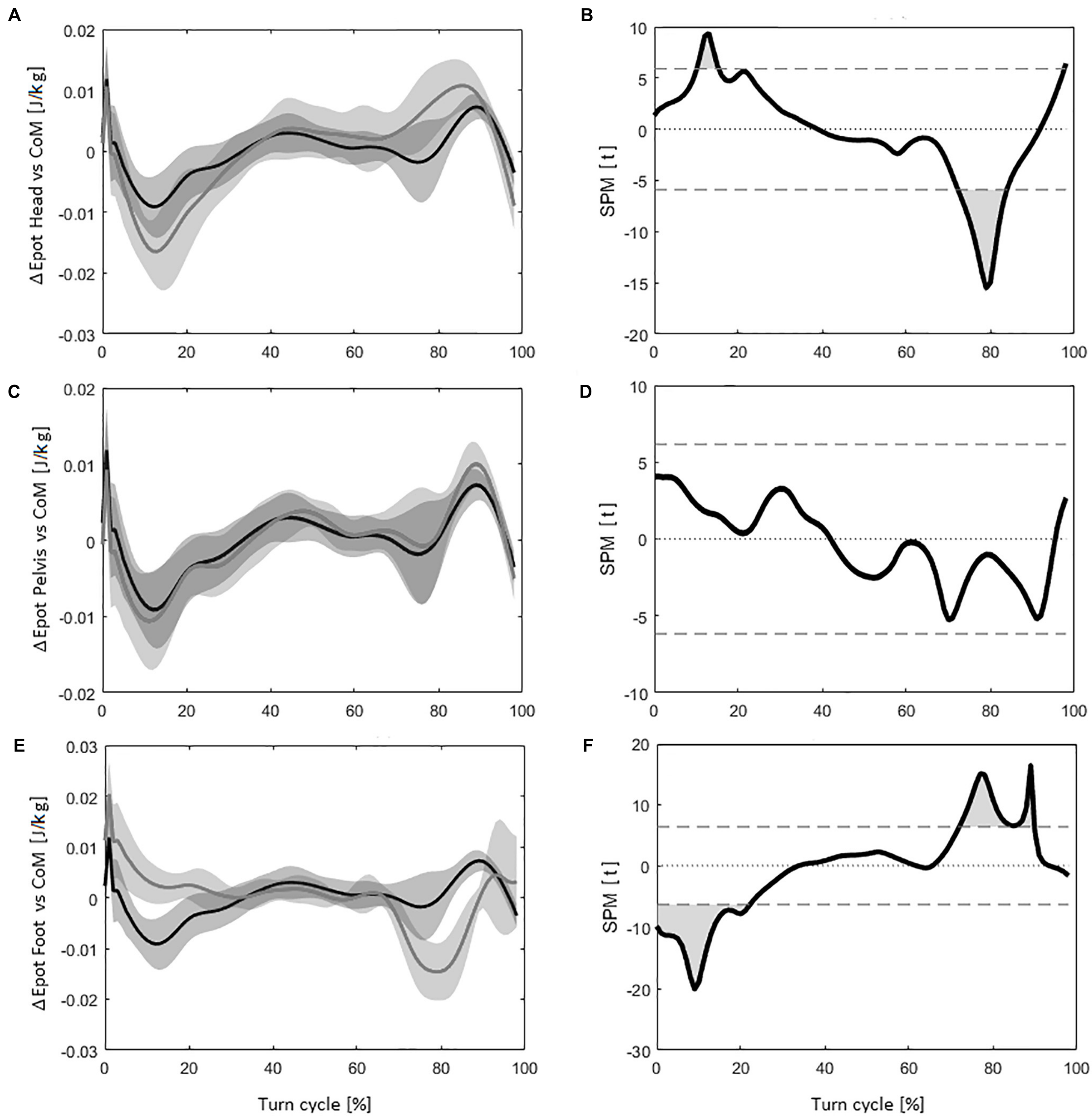


**FIGURE 2 | (A)** The evolution of the delta of potential energy (Δ*Epot*) for the *CoM* (in black) and the *Head* (in dark gray) during the turn cycle, with the corresponding standard deviation (*SD*) (in light gray). **(B)** Evolution of statistical parametric mapping (*SPM)* values (*tt*) during the turn cycle, with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Head* (the horizontal dash lines correspond to $tt = 6.79$, $p = 0.05$). **(C)** The evolution of Δ*Epot* for the *CoM* (in black) and the *Pelvis* (in dark gray) during the turn cycle, with the corresponding *SD* (in light gray). **(D)** Evolution of *SPM* values (*tt*), with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Pelvis.* **(E)** The evolution of Δ*Epot* for the *CoM* (in black) and the *Feet* (in dark gray) during the turn cycle, with the corresponding *SD* (in light gray). **(F)** Evolution of *SPM* values (*tt*), with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Feet*.

shows the evolution of the Δ*Epot* between the *CoM* and the *Pelvis* with the corresponding *SPM* curve on **Figure 2D** (*tt* threshold at ±6.16).

Concerning the use of the *Feet* to estimate the Δ*Epot*, 41% of the measures during the turn cycle had significantly different values (*tt* threshold at ±6.33) compared to the values obtained using the *CoM*, as seen in **Figures 2E,F**.

## Kinetic Energy

From the *Ekin* calculation, it can be seen that the *Head* induced significantly different values for 20% of the measures during the turn cycle compared to the results obtained using the *CoM*. **Figure 3A** represents the evolution of the curves during the turn cycle, while **Figure 3B** shows the corresponding SPM results (*tt* threshold at ±5.99). Compared to the *CoM*, the *Head* induced

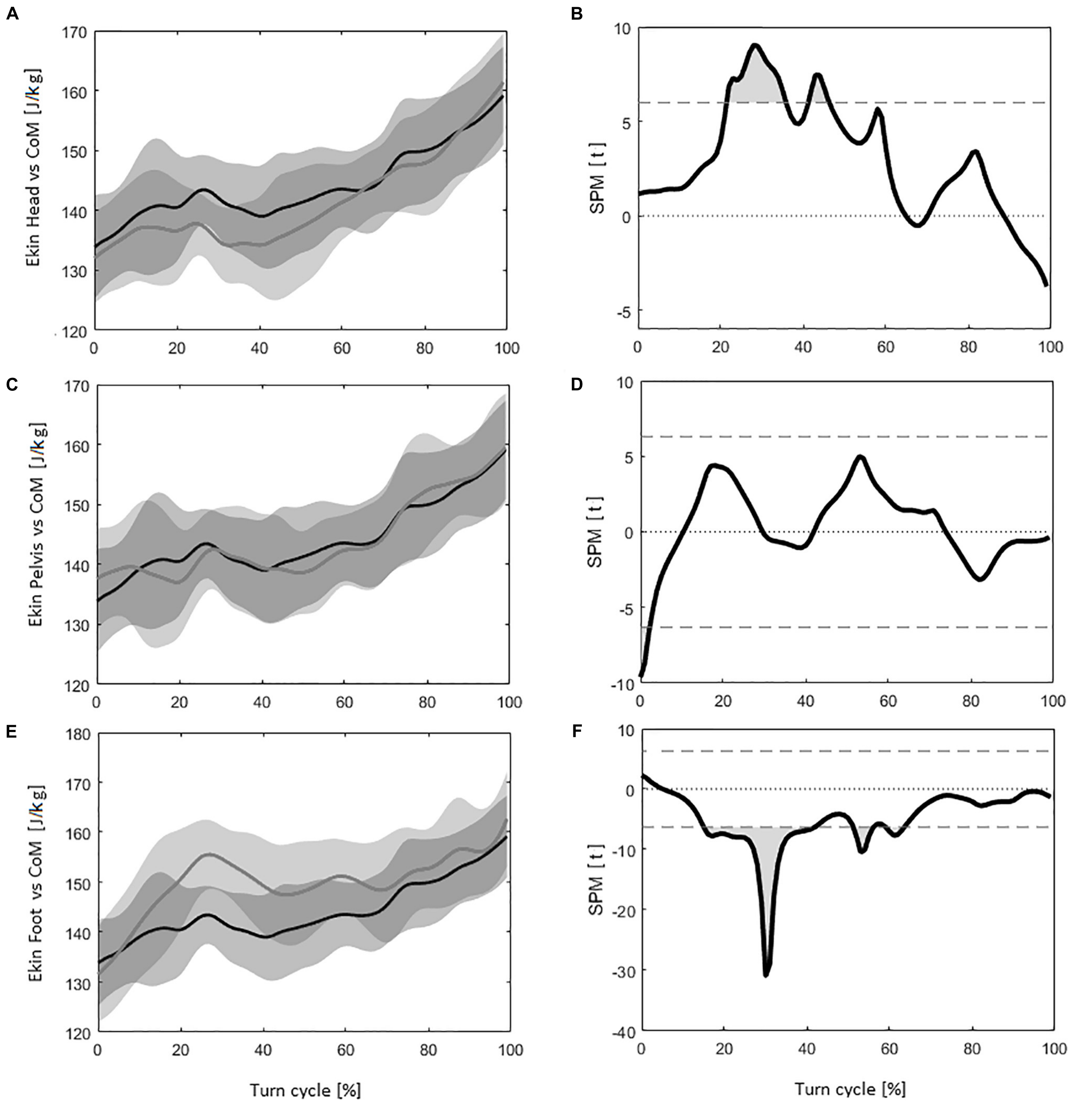


**FIGURE 3 | (A)** The evolution of the kinetic energy (*Ekin*) for the *CoM* (in black) and the *Head* (in dark gray) during the turn cycle, with the corresponding standard deviation (*SD*) (in light gray). **(B)** Evolution of statistical parametric mapping (*SPM*) values (*tt*) during the turn cycle, with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Head* (the horizontal dash lines correspond to *tt* = 6.79, *p* = 0.05). **(C)** The evolution of *Ekin* for the *CoM* (in black) and the *Pelvis* (in dark gray) during the turn cycle, with the corresponding *SD* (in light gray). **(D)** Evolution of *SPM* values (*tt*), with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Pelvis.* **(E)** The evolution of *Ekin* for the *CoM* (in black) and the *Feet* (in dark gray) during the turn cycle, with the corresponding *SD* (in light gray). **(F)** Evolution of *SPM* values (*tt*), with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Feet*.

a significant underestimation of $-2.57 \pm 1.22$ J/kg ($p < 0.001$) when calculating $Ekin_{\mathrm{m}}$.

Compared to the *CoM*, The *Pelvis* induced significantly different values for only 2% of the *Ekin* measurement during the turn cycle (**Figures 3C,D**) (*tt* threshold at $\pm 6.31$). No significant difference were found between the *CoM* and the *Pelvis* for $Ekin_{\mathrm{m}}$ ($-0.22 \pm 0.93$ J/kg, $p = 1.000$).

For the *Feet, Ekin* calculation led to significantly different values for 36% of the turn cycle compared to the *CoM*. **Figures 3E,F** displays the evolution of the *Ekin* curve and *SPM*

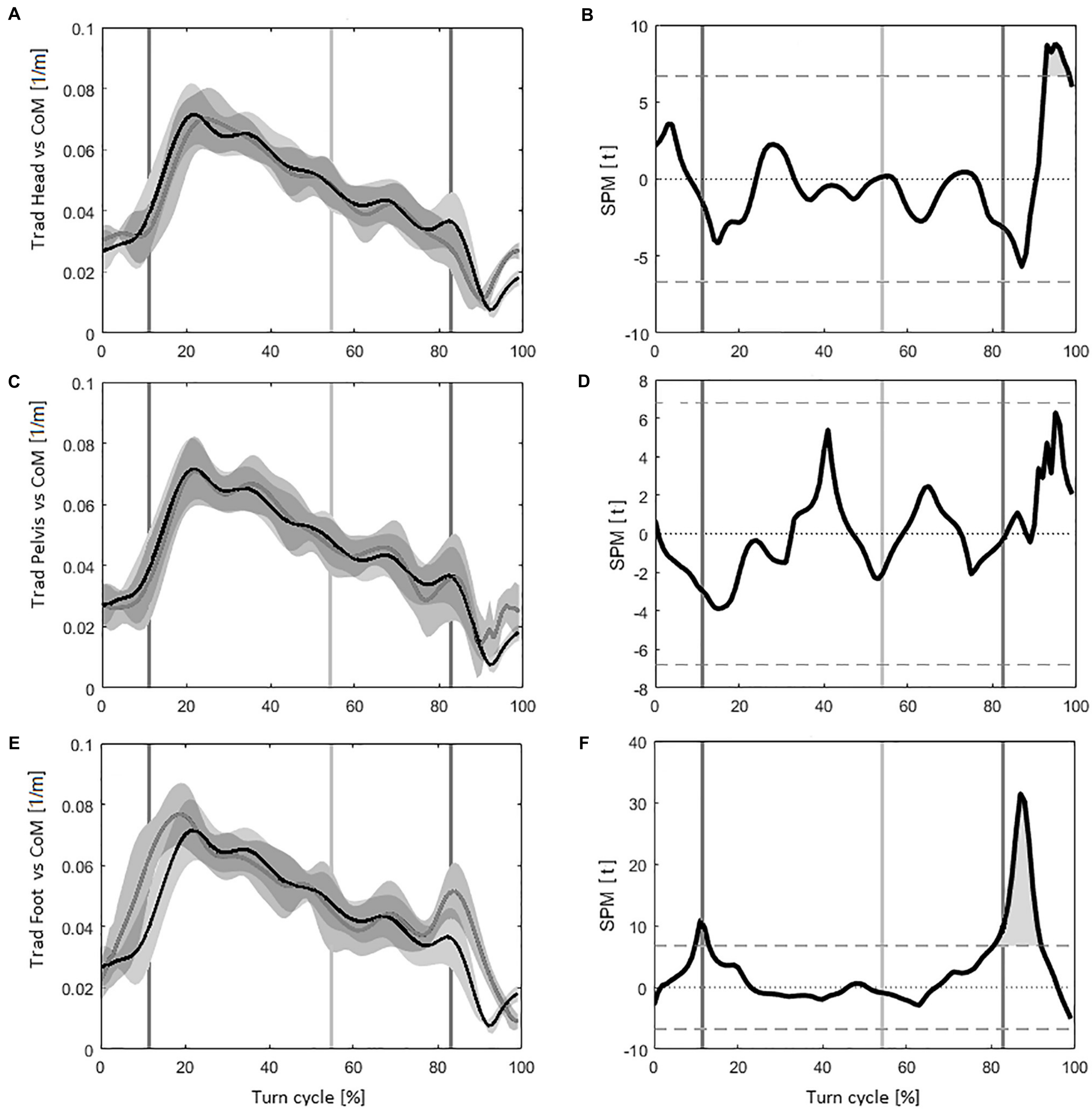


**FIGURE 4 | (A)** The evolution of the turn radius (*Trad*) for the *CoM* (in black) and the *Head* (in dark gray) during the turn cycle, with the corresponding standard deviation (*SD*) (in light gray). **(B)** Evolution of statistical parametric mapping (*SPM*) values (*tt*) during the turn cycle, with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Head* (the horizontal dash lines correspond to *tt* = 6.79, *p* = 0.05). **(C)** The evolution of *Trad* for the *CoM* (in black) and the *Pelvis* (in dark gray) during the turn cycle, with the corresponding *SD* (in light gray). **(D)** Evolution of *SPM* values (*tt*), with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Pelvis.* **(E)** The evolution of *Trad* for the *CoM* (in black) and the *Feet* (in dark gray) during the turn cycle, with the corresponding *SD* (in light gray). **(F)** Evolution of *SPM* values (*tt*), with light gray area representing the portions of the turns were it is statistically possible to differentiate the *CoM* with the *Feet*.

results (*tt* threshold at ±6.29). The *Feet* induced a significant overestimation of $Ekin_m$ [5.77 ± 4.00 J/kg ($p < 0.001$)] compared to the result obtained with the *CoM*.

## Turn Radius

The results obtained using the *Head* instead of the *CoM* for the calculation of *Trad* indicated significant differences for 7% of the turn cycle. Evolution of *Trad* is described in **Figure 4A**, with the corresponding SPM values **Figure 4B** (*tt* threshold at ±6.67).

The calculation of *Trad* using the *Pelvis* instead of the *CoM* induced no significant differences during the whole turn cycle (*tt* threshold at ±6.79). The corresponding curves are plotted on **Figures 4C,D**.

Using the *Feet* instead of the *CoM* to estimate *Trad* revealed that 16% of the measures had significantly different values during the turn cycle. **Figures 4E,F** displays the evolution of the *Trad* curve and *SPM* results for the comparison of the *CoM* and the *Feet* during the turn cycle (*tt* threshold at ±6.76).

Comparison of *Tentry* and *Texit* between the *CoM* and the morphological points can be found in **Table 1**.

# DISCUSSION

The most important finding of this study was the high level of agreement between the *Pelvis* and the *CoM*. Indeed, when looking at the different parameters analyzed, the *Pelvis* offered the best estimation for the Δ*Epot*, *Ekin* and *Trad* calculation. No significant differences were found for the Δ*Epot* and *Trad* during the whole turn whilst only 2% of the turn cycle significantly differed in the case of the *Ekin*. The difference was encountered only at the beginning of the turn.

As a global observation, it is quite intuitive to see the *Feet* and the *Head* as extreme points of the skier, while the *Pelvis* is more centered and near the *CoM*. Nevertheless, the *Head* allowed slightly better estimations than the *Feet* for the analyzed parameters showing more similar patterns of the *CoM*. The angulation of the hips during the second half of the turn can probably explain this result, as the *Head* is more centered vertically on the *CoM* while the *Feet* follow an external trajectory. The best morphological point to estimate Δ*Epot* and *Ekin* is therefore the *Pelvis*, followed by the *Head* and finally by the *Feet* that offer poor reliability.

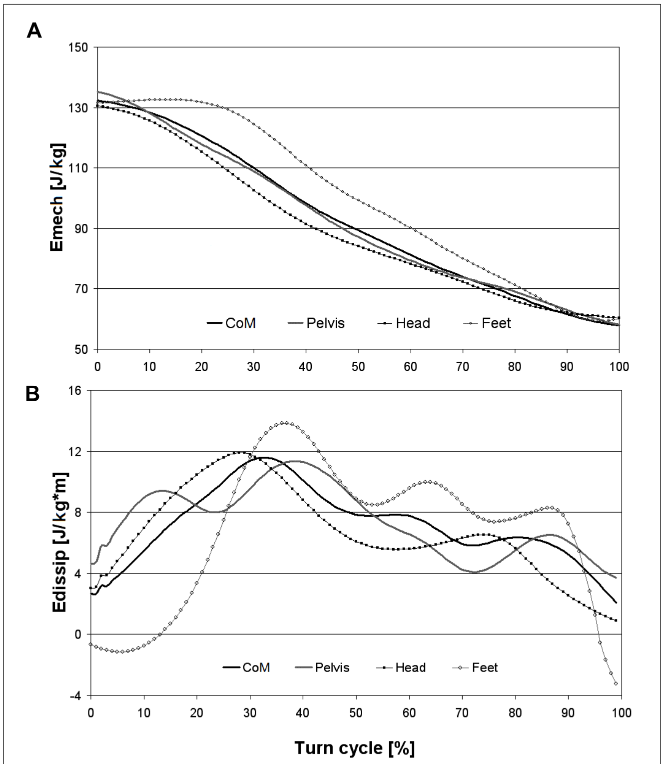


**FIGURE 5 | (A)** Mechanical energy (*Emech*) calculated using the CoM and the morphological points, **(B)** Energy dissipation (*Edissip*) during the turn.

## Energy

As *Epot* is directly correlated to vertical displacement, the curves of Δ*Epot* obtained in this study can be compared to the work proposed by Pozzo et al. (2005), who calculated the vertical displacement of the *CoM* compared to the ground. As expected, the *CoM* was higher during transitions between turns and lower at gate crossings. This corresponds well to the interpretation of Δ*Epot* curves calculated using the *CoM* and the *Feet* in the present study.

As the *Ekin* values depend on the square power of the speed, the shape of the curves obtained in this study can also be compared to those obtained by Pozzo et al. (2005) for the speed of the skiers during the turns. The measured speed attained its maximal value during gate transition, as it does in the present study.

**TABLE 1 |** Moment of the turn cycle (in %) when the radius falls below 25 m (Tentry) and exceed 25 m again (Texit).

| | Tentry mean ± SD [%] | Texit mean ± SD [%] |
|---|---|---|
| CoM | 12.33 ± 2.88 | 84.67 ± 2.58 |
| Head | 14.50 ± 3.02 | 74.67 ± 4.64* |
| Pelvis | 13.17 ± 3.19 | 13.17 ± 3.19 |
| Feet | 6.50 ± 3.02† | 90.50 ± 1.98† |

*Paired T-Test comparing CoM to Head, Pelvis and Feet.* **p* < 0.001, †*p* < 0.05.

Supej (2008) and Reid et al. (2009) analyzed the mechanical energy of skiers *(Emech)*, which involved addition of the *Ekin* and the *Epot*. They also calculated the corresponding dissipated energy *(Edissip)* as the change in mechanical energy per change of vertical distance (Supej et al., 2005). To allow comparison with these studies, **Figures 5A,B** show the *Emech* and the *Edissip* respectively, calculated using the *CoM* and the morphological points of the present study.

The curves obtained for the *CoM* are very similar to those obtained by Supej (2008) in *GS* and Reid et al. (2009) in slalom. The minimum energy dissipation occurred at the turn transition and the maximum during the first steering phase, between 20 and 40% of the turn cycle.

## Turn Radius

The *Trad* described by the *Feet* trajectory began earlier and ended after the *Trad* of the *CoM*. The *Head* also finished the turn earlier than the *CoM*. Therefore, the Head had the longer time interval between two turns where its trajectory was almost straight, and the Feet had the shortest time interval with a straight trajectory. It was interesting to note that around the gate crossing, inter-athlete variability increased, suggesting that the gates induced perturbation. If the radius decreased during the transition phase to reach its minimum, it increased gradually during the steering phases. Supej (2008) obtained a curve of a similar shape when calculating the *CoM*'s turn radius of four athletes performing *GS*. For slalom turns, Reid et al. (2009) obtained a different curve in slalom, where the radius decreased slowly during the first part of the turn and increased rapidly at the end of the turn. This indicates a different choice of trajectory in giant compared to slalom.

The *Feet* trajectory radii showed a small reduction between the second steering phase and the transition phase, when the skier decided to engender the new turn. It was at this same moment that the skier made a longitudinal extension, when the *Epot_diff* between the *CoM* and the *Head* increased, at approximately 80% of the turn cycle (**Figure 3A**).

Once again, the *Pelvis* gave the best approximation of the *CoM* concerning turn radius, followed by the *Head*. The *Feet*, with a time lag in the turn radius did not offer a good approximation of the *CoM*'s *Trad*, but it could be interesting to further explore the radius reduction around 85% of the turn. Indeed, it may be possible that this radius reduction coincides with an increase in the force and an extension of the skier to trigger the next turn.

## CONCLUSION

It is the first time that different morphological points of the body are used to estimate energetic parameters of alpine skiers. The results obtained with the *Pelvis* offered very accurate approximations of the *CoM*, with an equivalent accuracy than the pendulum method used by Gilgien et al. (2013). The *Head* also offered a good approximation for overall energy analysis and is a very accessible point for 3D video tracking or *GNSS* antenna placement, but side leaning profiles induced inaccurate estimations in the middle part of the turn. Finally, the *Feet* did not allow for a good estimation of the *CoM* as most of the parameters did not even have curves that look like those described by the *CoM*.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

## ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the HRO Guidelines from the "Commission cantonale (VD) d'éthique de la recherche sur l'être humain." The protocol was approved by the "Commission cantonale (VD) d'éthique de la recherche sur l'être humain." All subjects gave written informed consent in accordance with the Declaration of Helsinki.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

## FUNDING

This work was supported by a Grant from the Swiss Federal Office for Sports.

## ACKNOWLEDGMENTS

The authors wants to thanks the athletes for their participation to this study. Parts of the present manuscript were included in the Ph.D. thesis of the first author (Meyer, 2012).

## REFERENCES


Abdel-Aziz, Y. I., and Karara, H. M. (2015). Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. *Photogramm. Eng. Remote Sens.* 81, 103–107. doi: 10.14358/PERS.81.2.103

Barbier, F., Allard, P., Guelton, K., Colobert, B., and Godillon-Maquinghen, A.-P. (2003). Estimation of the 3-D center of mass excursion from force-plate data during. *IEEE Trans. Neural Syst. Rehabil.* 11, 31–37. doi: 10.1109/TNSRE.2003.810433

Belli, A., Avela, J., and Komi, P. V. (1993). Mechanical energy assessment with different methods during running. *Int. J. Sports Med.* 14, 252–256. doi: 10.1055/s-2007-1021173

Cavagna, G., Saibene, F. P., and Margaria, R. (1963). External work in walking. *J. Appl. Physiol.* 18, 1–9. doi: 10.1152/jappl.1963.18.1.1

Chèze, L., Fregly, B. J., and Dimnet, J. (1995). A solidification procedure to facilitate kinematic analyses based on video system data. *J. Biomech.* 28, 879–884. doi: 10.1016/0021-9290(95)95278-D

Clauser, C. E., McConville, J. T., and Young, J. W. (1969). *Weight, Volume, and Center of Mass of Segments of the Human Body*. Final Report, No. TR-69-70. Fort Belvoir, VA: Defense Technical Information Center.

De Leva, P. (1996). Adjustments to zatsiorsky-seluyanov's segment inertia parameters. *J. Biomech.* 29, 1223–1230. doi: 10.1016/0021-9290(95)00178-6

Fasel, B., Spörri, J., Gilgien, M., Boffi, G., Chardonnens, J., Müller, E., et al. (2016). Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors. *Remote Sens.* 8:671. doi: 10.3390/rs8080671

Frenet, F. (1852). Sur les courbes à double courbure. *J. Math.* 17, 437–447.

Gard, S. A., Miff, S. C., and Kuo, A. D. (2004). Comparison of kinematic and kinetic methods for computing the vertical motion of the body center of mass during walking. *Hum. Mov. Sci.* 22, 597–610. doi: 10.1016/j.humov.2003.11.002

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gomez-Lopez, P. J., Hernan, O., and Ramirez, J. V. (2009). "Analysis of skiers' performance using GPS," in *Science and Skiing IV*, eds E. Müller and T. Stöggl (Maidenhead: Meyer & Meyer Sport), 207–215.

Greville, T. (1964). Numerical procedures for interpolation by spline functions. *J. Soc. Ind. Appl. Math. B Numer. Anal.* 1, 53–68.

Hanavan, E. P. (1964). A mathematical model of the human body. AMRL-TR-64-102. *AMRL TR*, 1–149.

Hatze, H. (1988). High-precision three-dimensional photogrammetric calibration and object space reconstruction using a modified DLT-approach. *J. Biomech.* 21, 533–538. doi: 10.1016/0021-9290(88)90216-3

Kagawa, H. Y. T. (2001). "Effective action of skier's center of mass in skiing," in *Science and Skiing II*, eds H. S. E. Müller, C. Raschner, S. Lindinger, and E. Kornexl (Oxford: Meyer & Meyer Sport).

Kyröläinen, H., Belli, A., and Komi, P. (2001). Biomechanical factors affecting running economy. *Med. Sci. Sports Exerc.* 33, 1330–1337. doi: 10.1097/00005768-200108000-00014

Lee, S., Wolberg, G., and Shin, S. Y. (1997). Scattered data interpolation with multilevel b-splines. *IEEE Trans. Vis. Comput. Graph.* 3, 228–244. doi: 10.1109/2945.620490

Lešnik, B., and Zvan, M. (2003). Comparison of centre of mass trajectories in modern giant slalom techniques. *Kinesiology* 35, 191–200.

Meyer, F. (2012). *Biomechanical Analysis of Alpine Skiers Performing Giant Slalom Turns.* Ph.D. thesis, Univ. Lausanne, Lausanne.

Meyer, F., Bahr, A., Lochmatter, T., and Borrani, F. (2012). Wireless GPS-based phase-locked synchronization system for outdoor environment. *J. Biomech.* 45, 188–190. doi: 10.1016/j.jbiomech.2011.09.014

Pataky, T. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J. Biomech.* 43, 1976–1982. doi: 10.1016/j.jbiomech.2010.03.008

Pataky, T., Vanrenterghem, J., and Robinson, M. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J. Biomech* 48, 1277–1285. doi: 10.1016/j.jbiomech.2015.02.051

Pozzo, R., Canclini, A., Cotelli, C., and Barroni, G. (2005). "3D kinematics and kinetic analysis of geant slalom in elite skiers at Val Badia world cup race in 2002," in *Science and Skiing III*, eds D. B. E. Müller, R. Klika, S. Lindinger, and H. Schwameder (Oxford: Meyer & Meyer Sport (Uk), Ltd), 125–135.

Reid, R., Gilgien, M., Moger, T., Tjorhom, H., Haugen, P., Kipp, R., et al. (2009). "Turn characteristics and energy dissipation in slalom," in *Science and Skiing IV*, eds S. L. E. Müller and T. Stöggl (Maidenhead: Meyer & Meyer Sport), 419–429.

Richards, J. G. (1999). The measurement of human motion: a comparison of commercially available systems. *Hum. Mov. Sci.* 18, 589–602. doi: 10.1016/S0167-9457(99)00023-8

Saibene, F., and Minetti, A. E. (2003). Biomechanical and physiological aspects of legged locomotion in humans. *Eur. J. Appl. Physiol.* 88, 297–316. doi: 10.1007/s00421-002-0654-9

Schiefermüller, C., Lindinger, S., and Mueller, E. (2005). "The skier's centre of gravity as a reference point in movement analysis for different designated systems," in *Science and Skiing III*, eds D. B. E. Müller, R. Klika, S. Lindinger, and H. Schwameder (Aachen: Meyer & Meyer Sport), 172–185.

Serret, J. A. (1851). Sur quelques formules relatives à la théorie des courbes à double courbure. *J. Math.* 16, 193–207.

Slawinski, J., Billat, V., Koralsztein, J. P., and Tavernier, M. (2004). Use of lumbar point for the estimation of potential and kinetic mechanical power in running. *J. Appl. Biomech.* 20, 324–331. doi: 10.1123/jab.20.3.324

Supej, M. (2008). Differential specific mechanical energy as a quality parameter in racing alpine skiing. *J. Appl. Biomech.* 24, 121–129. doi: 10.1123/jab.24.2.121

Supej, M., Kugovnik, O., and Nemec, B. (2005). "Energy principle used for estimating the quality of a racing ski turn," in *Science and Skiing III*, eds D. B. E. Müller, R. Klika, S. Lindinger, and H. Schwameder (Aachen: Meyer & Meyer Verlag), 228–237.

Terrier, P., Turner, V., and Schutz, Y. (2005). GPS analysis of human locomotion: Further evidence for long-range correlations in stride-to-stride fluctuations of gait parameters. *Hum. Mov. Sci.* 24, 97–115. doi: 10.1016/j.humov.2005.03.002

Waegli, A., Meyer, F., Ducret, S., Skaloud, J., and Pesty, R. (2009). "Assessment ot timing and performance based on trajectories from low-cost GPS/INS positioning," in *Science and Skiing IV*, eds S. L. E. Müller and T. Stöggl (Maidenhead: Meyer & Meyer Sport), 556–564.

Waegli, A., and Skaloud, J. (2007). "Assessment of GPS/MEMS-IMU integration performance in ski racing," in *Proceedings of the ENC GNSS* 2007 (TimeNav'07), Geneva.

Waegli, A., and Skaloud, J. (2009). Optimization of two GPS/MEMS-IMU integration strategies with application to sports. *GPS Solut.* 13, 315–326. doi: 10.1007/s10291-009-0124-5

Willems, P. A., Cavagna, G. A., and Heglund, N. C. (1995). External, internal and total work in human locomotion. *J. Exp. Biol.* 198, 379–393.

World Medical Association (2013). World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. *JAMA* 310, 2191–2194. doi: 10.1001/jama.2013.281053

Zatsiorsky, V. S. V. (1983). "The mass and inertia characteristics of the main segments of the human body," in *Biomechanics VIII-B*, eds H. Matsui and K. Kobayashi (Champaign, IL: Human Kinetics), 1152–1159.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

PERSPECTIVE
published: 02 July 2018
doi: 10.3389/fphys.2018.00796

# The Olympic Biathlon – Recent Advances and Perspectives After Pyeongchang

*Marko S. Laaksonen[1]*, Malin Jonsson[1] and Hans-Christer Holmberg[1,2,3]*

[1] Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Östersund, Sweden, [2] School of Sports Sciences, UiT The Arctic University of Norway, Tromsø, Norway, [3] School of Kinesiology, The University of British Columbia, Vancouver, BC, Canada

The biathlon, combining cross-country ski skating with rifle marksmanship, has been an Olympic event since the Winter Games in Squaw Valley, United States, in 1960. As a consequence of replacing the classical with the skating technique in the 1980s, as well as considerable improvements in equipment and preparation of ski tracks and more effective training, the average biathlon skiing speed has increased substantially. Moreover, the mass-start, pursuit, and sprint races have been introduced. Indeed, two of the four current individual Olympic biathlon competitions involve mass-starts, where tactics play a major role and the outcome is often decided during the last round of shooting or final sprint. Biathlon is a demanding endurance sport requiring extensive aerobic capacity. The wide range of speeds and slopes involved requires biathletes to alternate continuously between and adapt different skating sub-techniques during races, a technical complexity that places a premium on efficiency. Although the relative amounts of endurance training at different levels of intensity have remained essentially constant during recent decades, today's biathletes perform more specific endurance training on roller skis on terrain similar to that used for competition, with more focus on the upper-body, systematic strength and power training and skiing at higher speeds. Success in the biathlon also requires accurate and rapid shooting while simultaneously recovering from high-intensity skiing. Many different factors, including body sway, triggering behavior, and even psychology, influence the shooting performance. Thus, the complexity of biathlon deserves a greater research focus on areas such as race tactics, skating techniques, or shooting process.

**Keywords: performance, physiology, shooting, skiing, training**

OPEN ACCESS

***Edited by:***
*Gregoire P. Millet,*
*Université de Lausanne, Switzerland*

***Reviewed by:***
*Laurent Schmitt,*
*Centre National de Ski Nordique et de Moyenne Montagne, France*
*Thomas Maier,*
*Swiss Federal Institute of Sport Magglingen SFISM, Switzerland*

****Correspondence:***
*Marko S. Laaksonen*
*marko.laaksonen@miun.se*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *26 April 2018*
***Accepted:*** *06 June 2018*
***Published:*** *02 July 2018*

***Citation:***
*Laaksonen MS, Jonsson M and Holmberg H-C (2018) The Olympic Biathlon – Recent Advances and Perspectives After Pyeongchang. Front. Physiol. 9:796. doi: 10.3389/fphys.2018.00796*

## INTRODUCTION

The biathlon, an Olympic sport that combines rifle marksmanship and cross-country (XC) skiing with the skating technique while carrying a rifle, involves considerable physiological demands similar to those associated with competitive XC skiing (Hoffman and Street, 1992; Sandbakk and Holmberg, 2014; Holmberg, 2015), while also requiring precise fine motor control for fast and accurate shooting under mental pressure (Vickers and Williams, 2007). Moreover, this challenging endurance sport entails alternating between various sub-techniques that require different relative amounts of upper- and/or lower-body work while skiing on varying terrain. This necessitates extensive training designed not only to optimize the relevant physiological capacities and performance of various ski skating techniques, but also to improve and maintain accurate shooting within a short period of time.

## The Evolution of Olympic Biathlon Competition

The biathlon first became an Olympic event in the Winter Games in Squaw Valley, United States, in 1960. The development of the skating technique in the 1980s (Smith, 1990), in combination with substantial improvements in equipment, track preparation, and training, has increased the average skiing speeds in biathlon races considerably (IBU, 2018). Moreover, new events such as the sprint, pursuit, and mass-start have been introduced.

The recent Olympic Games in Pyeongchang in 2018 involved six types of biathlon races (**Table 1**), three of which were added after the Olympic Games in Nagano in 1998 – the pursuit competitions in 2002 at Salt Lake City, the mass-start in 2006 at Turin, and the mixed relay in 2014 at Sochi.

# THE DEMANDS OF OLYMPIC BIATHLON COMPETITION

Although the duration of biathlon races ranges from 20 min (the sprint) to more than 50 min (the individual race), seven of the 11 Olympic events (including relays) involve mass-starts, which enhance the importance of tactics and where the outcome is often decided by the last round of shooting and/or the final skiing sprint. The overall performance in the biathlon is complex, being decided by several components, such as skiing speed, range time (time spent on the shooting ramp), shooting time, and shooting accuracy. Usually, the range and shooting times of elite biathletes and in different types of competitions are similar and, thus, exert only a minor impact on the final performance. In contrast, skiing speed and shooting accuracy are the most important determinants of the final outcome (Skattebo and Losnegard, 2018).

## Skiing

The biathlon race courses are required to consist of continuously changing flat, uphill, and downhill sections (IBU, 2017), forcing frequent alternation between the various skating sub-techniques (Holmberg, 2015). The demands of biathlon skiing are comparable to those made by XC skiing, where more than 50% of the racing time is spent on uphill terrain, the sections on which individual performance varies most (Bergh and Forsberg, 2000; Andersson et al., 2010; IBU, 2018). World-class male and female biathletes demonstrate high maximal oxygen uptakes ($VO_2max$) of >80 and >65 mL·kg$^{-1}$·min$^{-1}$, respectively (Tønnessen et al., 2015). The best competitors are well-trained endurance athletes, excellent at skiing with the skating technique, and, in several cases, also able to compete at a high level in elite XC ski races.

In addition to adapting their speed to the track profile, snow conditions, and altitude, biathletes (in contrast to XC skiers) must prepare for the coming shooting. Thus, unlike XC skiing, biathlon skiing is intermittent, being interrupted by short stops on the

**TABLE 1** | The different types of biathlon competition at the Pyeongchang Olympic Games in 2018.

| Competition | Type of start | Skiing distance (km) | Shooting | Competition time (mm:ss) | Skiing time (mm:ss) | Range time (mm:ss) | Shooting time (mm:ss) | Type of penalty | Duration on the penalty loop (s) |
|---|---|---|---|---|---|---|---|---|---|
| Sprint | Single-start | W: 7.5 (3 × 2.5)<br>M: 10 (3 × 3.3) | P+S | W: 20:00–23:00<br>M: 22:30–26:30 | W: 18:00–20:30<br>M: 21:00–24:30 | W: 1:30–2:00<br>M: 1:20–1:50 | W: 0:50–1:10<br>M: 0:50–1:05 | Penalty loop (150 m) | W: 23.0–26.0<br>M: 19.5–22.5 |
| Pursuit | Mass-start based on results of the sprint | W: 10 (5 × 2)<br>M: 12.5 (5 × 2.5) | P+P+S+S | W: 30:00:34:00<br>M: 31:00–33:30 | W: 25:30–29:30<br>M: 26:30–29:00 | W: 3:10–3:40<br>M: 2:50–3:15 | W: 1:45–2:15<br>M: 1:40–2:10 | Penalty loop (150 m) | W: 23.0–26.0<br>M: 19.5–22.5 |
| Mass-start | Mass-start | W: 12.5 (5 × 2.5)<br>M: 15 (5 × 3) | P+P+S+S | W: 34:00–37:30<br>M: 36:00–38:30 | W: 30:00–33:30<br>M: 32:00–34:00 | W: 3:10–3:30<br>M: 2:45–3:10 | W: 1:45–2:10<br>M: 1:35–2:00 | Penalty loop (150 m) | W: 23.0–26.0<br>M:19.5–22.5 |
| Individual | Single-start | W: 15 (5 × 3)<br>M: 20 (5 × 4) | P+S+P+S | W: 41:30–43:00<br>M: 44:30–48:00 | W: 37:30–39:00<br>M: 40:30–44:30 | W: 3:15–3:45<br>M: 3:00–3:30 | W: 1:50–2:20<br>M: 1:45–2:15 | Penalty time (1 min) | NA |
| Relay | Mass-start | W: 4 × 6 (3 × 2)<br>M: 4 × 7.5 (3 × 2.5) | 4 × P+S | W: 4 × 17:30–19:00<br>M: 4 × 18:30–20:30 | W: 4 × 15:00–16:30<br>M: 4 × 16:30–18:00 | W: 4 × 1:30–2:30<br>M: 4 × 1:30–2:30 | W: 4 × 0:50–2:00<br>M: 4 × 0:50–2:00 | Penalty loop (150 m) | W: 23.0–26.0<br>M: 19.5–22.5 |
| Mixed Relay | Mass-start | W: 2 × 6 (3 × 2) +<br>M: 2 × 7.5 (3 × 2.5) | 4 × P+S | W: 2 × 16:00–18:30 +<br>M: 2 × 18:00–19:30 | W: 2 × 14:00–16:30 +<br>M: 2 × 16:00–17:30 | W: 4 × 1:30–2:15<br>M: 4 × 1:30–2:15 | W: 4 × 0:50–1:30<br>M: 4 × 0:50–1:30 | Penalty loop (150 m) | W: 23.0–26.0<br>M:19.5–22.5 |

*W, women; M, men; P, prone position; S, standing position; NA, not applicable.*

shooting range. It has been proposed that that skiing speed is responsible for more than 60% of the overall performance in World Cup biathlon sprint competitions (Luchsinger et al., 2018), but it is currently unknown how the skiing speed influences the overall performance in different types of biathlon competitions or on different terrains. It is to be expected that in connection with pursuit and mass-start races, the skiing speed exerts less impact on the overall performance than in sprint, since the former events involve four bouts of shooting with shorter skiing loops between. During mass-start races, drafting behind other skiers, locating oneself optimally in the crowd also helps maximize the utilization of individual strengths.

From a biomechanical perspective, biathletes resemble XC skiers, employing a wide range of speeds over varying terrain with continuous transitions between the different sub-techniques (Andersson et al., 2010), also called gears[1], as well as utilizing the tuck position and several different turning techniques downhill (Sandbakk Ø. et al., 2014; Sandbakk S.B. et al., 2014). These many transitions between gears require not only mastery of the various skating sub-techniques, but also effective timing. Ski skating at the racing speed requires both long and rapid cycles (Stöggl and Müller, 2009; Stöggl et al., 2011; Sandbakk et al., 2012), with length being especially important on flat terrain and rapid cycles, with as little reduction in cycle length as possible, on steep uphill terrain and during the final sprint. The technical complexity involved, with numerous possibilities for timing the generation of force by the arms and legs, offers both opportunities and presents challenges. To date, few investigations have considered how carrying a rifle (minimum weight 3.5 kg) while skiing influences energy cost/skiing physiology and biomechanics (Rundell and Szmedra, 1998; Stöggl et al., 2015), as well as the choice of sub-technique.

## Shooting

Overall, the shooting accuracies in the prone and standing positions are comparable, probably because of the difference in the diameter of the target hit areas (4.5 versus 11.5 cm, respectively; IBU, 2018). In the Sochi Olympic Games in 2014, the average shooting accuracy for all individual male and female medalists was 97%. Under the more difficult wind conditions encountered in the recent Pyeongchang Games, the corresponding values were 93 and 95%, respectively. However, this level of accuracy is actually greater than the long-term accuracy of these same athletes, indicating a high degree of randomness in connection with biathlon shooting (Maier et al., 2018). Altogether, if a biathlete hopes to win an Olympic medal under normal weather conditions, he/she cannot miss even once during the two rounds of shooting in sprint races and incur no more than one penalty in connection with the four shootings in the other individual events.

During the 15–30 s prior to shooting, the biathlete slows down slightly, with the duration of this slowdown being highly individual and dependent on the terrain. After stopping in the shooting lane, the biathlete takes the position and fires the first shot within 15 s, the entire series of five shots lasting approximately 10 s. During this time, the heart rate usually falls from approximately 90 to 60 or 70% of $HR_{max}$ during prone or standing shooting, respectively (Hoffman and Street, 1992). However, the intensity of exercise prior to shooting has been proposed to have only a minimal impact on the shooting performance (Hoffman et al., 1992).

The necessity to prepare, fire five shots, and exit the shooting lane within approximately 25–30 s is highly stressful. However, the time spent on the shooting range and shooting time varies relatively little between elite biathletes and, therefore, contributes to the overall performance to only a minor extent (∼2–4%; Luchsinger et al., 2018; Skattebo and Losnegard, 2018). At the same time, approximately 35% of the overall biathlon sprint performance is determined by shooting accuracy (Luchsinger et al., 2018), a value that may be as high as 50% in connection with individual biathlon races, where each missed shot results in a 1-min penalty.

Several aspects of the shooting technique influence the performance. In the prone position, the triggering behavior and rifle sway of world-class biathletes distinguish them from lower level competitors, and rifle sway is also an important factor in the standing position (Sattlecker et al., 2017). The preceding exercise almost certainly influences the psychophysiological aspects of the arousal/activation and focused attention required to perform the complex task of aiming successfully, since the several tasks (aiming, maintaining optimal body posture, and triggering) performed simultaneously demand extensive fine-motor control. A more in-depth systematic analysis of the biomechanics of shooting in both the prone and standing positions under pronounced stress needs to be performed.

Weather conditions, and especially wind, exert a considerable impact on the shooting strategy. Although the wind speed appears to exert only a minor effect on the overall shooting accuracy (Skattebo and Losnegard, 2018), the wind must be taken into consideration and sometimes the biathlete must wait until the wind subsides. In addition, when shooting in standing position, depending on the layout of the stadium, it can be beneficial to shoot from lanes where the wind is lighter and affects body sway less. Thus, future studies in biathlon shooting should also assess the effects of weather conditions, including temperature, wind (especially speed and direction), and visibility (snowfall and fog).

# TRAINING FOR OLYMPIC BIATHLON RACES

The best biathletes perform 700–900 h of physical training annually, including endurance training of approximately 80% at low, 4–5% at moderate, and 5–6% at high intensity, together with 10% of strength and speed training (**Table 2**; personal communication with Swedish biathlon coaches). This volume of training is slightly less than that reported earlier for XC skiers (Sandbakk and Holmberg, 2014), probably due to the time spent on training shooting. Usually, exercise intensities are chosen on

[1] Gear 2 (also referred to as V1 skate or offset skate, used primarily on moderate to steep terrain); Gear 3 (or V2 skate or double time, used mainly on level to moderate uphill terrain); Gear 4 (or V2 alternate skate or single time, used mostly on level terrain).

**TABLE 2** | Overview of training by the successful Swedish biathletes who won medals at the Pyeongchang Olympic Games in 2018.

| Physical training | Shooting training |
|---|---|
| In total, 700–900 h of endurance training | In total, ~22 000 shots fired during ~210 sessions |
| 550–700 h training at low intensity (60–80 % $HR_{max}$) | ~7000 shots at rest (during ~45 sessions from May to the middle of August) |
| 30–45 h training at moderate intensity (80-90 % $HR_{max}$) | 2400 shots for training precision (~20 sessions) |
| 35–50 h training at high intensity, including races (>90% $HR_{max}$) | 2400 shots for training under stress (~24 sessions) |
| 10–15 sessions of anaerobic lactic acid training | 120–130 sessions "dry shooting" |
| 10–15 sessions of speed/power training | 2000–3000 shots to zero the rifle (training and competition combined) |
| 40–50 sessions of maximal or explosive strength training | ~12 000 shots in combination with physical training [A1–A3 (roller-)skiing, running] |
| 40–45 sessions of body stability/muscle activation strength training | ~700 shots during competitions |

the basis of laboratory testing and approximately 60–70% of the annual training is performed from May to November and the remainder during the competitive season from December to April. The season starts with more low-intensity training and the relative portions of moderate- and high-intensity training increase as the training season progresses. Roller skiing, cycling, and running on varying terrain are the predominant modes from May to October, with only a few days of training on snow each month, whereas from November onward, most training involves skiing on snow. The main technique is skating, with classical skiing being performed only during long sessions at low intensity or for recovery.

## Distribution of the Intensity of Training

Low-intensity training has been proposed to enhance overall aerobic capacity and exercise efficiency, as well as to improve "tolerance" for high training loads by accelerating recovery (Tønnessen et al., 2014). Although most low-intensity training is designed to develop aerobic capacity and/or specific motor skills, the inclusion of some semi- or un-specific training (e.g., cross-training) allows more overall exercise to be performed.

Training at moderate intensity (i.e., directly below the anaerobic threshold) can be prolonged while maintaining an adequate supply of aerobic energy. Such sessions commonly include long intervals of exercise, interspersed with short periods of recovery, or continuous exercise for 30–60 min. To control the intensity, such training is carried out preferably on a relatively constant terrain. Moderate-intensity training is performed once or twice a week during the period of preparation and less often during the competitive season.

Although the best athletes focus on extensive low-intensity training, the beneficial effects of high-intensity training on endurance performance have been demonstrated repeatedly (Laursen and Jenkins, 2002). At the same time, there is increasing awareness that highly trained athletes should focus more on improving the quality of each high-intensity session (i.e., optimization of physical, technical, and mental aspects) than on the number of such sessions.

## The Mode of Exercise

While their high-intensity training involves pre-dominantly roller-skiing and skiing, biathletes vary their low-intensity exercise considerably. During the 6 months of preparation, a biathlete gold medalist devotes 50–60% of his/her time to sport-specific training and most of the remainder to cycling and, to lesser extent, running (M. Laaksonen, personal communication, March 21, 2018). Biathletes presumably cycle more than XC skiers, since the former employs only the skating technique, which activates the legs (thighs) more extensively. While training (roller-) skiing in combination with shooting, biathletes may also carry a rifle on their back, but this is done surprisingly little (15–20% of all endurance training) and, thus, offers a considerable opportunity for future development.

In addition, biathletes must perform various skating techniques, which load the upper and lower body to different extents, efficiently. The choice of sub-technique is influenced by the speed and external conditions (e.g., the profile of the terrain, snow conditions, waxing of skis, and altitude), as well as the individual level of performance and physical characteristics. For example, since 50% of racing time is spent skiing uphill, training these sub-techniques is especially important. Overall, biathletes must be aware not only of the mode and intensity of their exercise, but also of how they train the arms, legs, and entire body.

## Training Speed and Strength

The increase in biathlon skiing speed during the last 20 years has involved an enhanced development of speed and strength. Thus, both male and female world-class biathletes train skiing speed, often in sessions involving 10–20 sprints at maximal intensity (depending on technique and terrain) with 2–3-min intervals of recovery.

However, to date, the effects of strength training on biathlon performance have not been documented. Several studies on XC skiers have revealed that movement-specific training of maximal upper body strength improves, in particular, double poling (Nilsson et al., 2004), although this technique is not used on its own in the biathlon. Overall, available findings allow us to speculate that for biathletes who train endurance extensively, additional training of strength and speed could develop and maintain muscle mass and power, particularly in the case of the upper body of women (Holmberg, 2005; Hegge et al., 2016), as well as improve the skating technique while carrying the rifle. However, the potential effects of combined speed and endurance training require considerably more evaluation.

## Training Shooting

The shooting time between bouts of skiing, usually 25–30 s in both the prone and standing positions, includes preparation (10–15 s for taking position), shooting (10–15 s for aiming and firing five shots), and exit (3–5 s). During a single season, world-class biathletes fire more than 20,000 shots during more than 200 training sessions, approximately 60% of which involve shooting combined with endurance training [9,000 (75%) at low, 2,000 (15%) at moderate, and 1,250 (10%) at high intensity], i.e., shooting between bouts of skiing or, to lesser extent, running (**Table 2**). Although the basics of such training have not changed significantly in recent decades, the shooting time and accuracy have tended to improve, emphasizing the importance of training under conditions that resemble those in a competition (e.g., biathlete against biathlete or under time pressure).

The remainder of these more than 20,000 shots are fired at rest, focusing on improving the accuracy and/or the speed of preparation, shooting, and exit. Indeed, many world-class biathletes now focus especially on preparing rapidly for the first shot and leaving the shooting lane as quickly as possible. Shooting at rest as well as shooting without ammunition (so-called dry shooting) can also improve triggering behavior, rifle stability, and/or holding (Groslambert et al., 2003), as well as mental aspects of shooting (Laaksonen et al., 2011). Thus, training under conditions that resemble competitive shooting is recommended for elite biathletes, not only to improve the accuracy but also to minimize the loss of time on the range and while shooting. Usually, preparation begins with shooting at rest (May), later progressing to shooting in connection with endurance training (June to November).

Outdoor conditions also influence the accuracy of biathlon shooting. Accordingly, training under windy conditions is recommended, since when shooting in the standing position rifle stability is strongly correlated to scores (Groslambert et al., 1999) and discriminates low- from high-scoring biathletes (Sattlecker et al., 2017). Moreover, rifle motion and body sway are related (Ihalainen et al., 2018), the latter being less pronounced in elite athletes (Niinimaa and McAvoy, 1983) and also clearly distinguishing low- from high-level shooters (Groslambert et al., 1999). Thus, balance training in connection with shooting is also beneficial for biathletes, as in the case of rifle shooters (Era et al., 1996).

In addition, trigger force prior to firing discriminates between elite and young athletes shooting while standing (Sattlecker et al., 2009). In general, exercise prior to shooting lessens this trigger force, but interestingly, elite biathletes are capable of maintaining their high pre-shot trigger force at rest even immediately after exercise (Sattlecker et al., 2013).

## FUTURE PERSPECTIVES

The current Olympic biathlon program will not be changed in connection with the next several Olympic Games, so the associated demands will probably not change as much as in previous years. However, since the skiing speed and shooting time of Olympic medalists are relatively similar, the shooting accuracy better than the biathlete's long-term average will become even more important in the future. The physiology and biomechanics of biathletes have been investigated much less extensively than those of XC skiers and, moreover, relatively little is known about actual competitions.

Recent advances in sensor technology allow the position, speed, kinematics, and kinetics of biathletes to be recorded in real time on the track, providing more detailed information concerning the determinants of success in the Olympic Games. Furthermore, the enhanced complexity of both physiological (unaltered aerobic, but more pronounced anaerobic demands) and technical training (a large number of sub-techniques to master, improved shooting technique) by modern biathletes accentuates inter-individual variations in adaptation and response. In addition, pacing strategies in different types of biathlon races, as well as the potential effects of pacing and exercise on shooting performance require examination. Furthermore, more comprehensive analysis of the shooting process, especially during actual competition, will help formulate training guidelines for future Olympic champions. However, the need to increase biathlon-specific training while carrying a rifle and to match training precisely to the unique characteristics of each individual biathlete will continue to challenge researchers for years to come.

Although much of the extensive literature on XC skiing and rifle shooting may be relevant to the biathlon, carrying a rifle while skiing and shooting under physiological and psychological stress are somewhat unique features. The number of publications about XC skiing is approaching 700 (April 19, 2018), while those on the biathlon have risen from 29 in 2006 (the Olympic Games in Turin) to almost 80 in 2018 (the Olympics Games in Pyeongchang). Although much of this latter research has focused on shooting and medical aspects, the last decade has seen a clear trend toward more interest in physiology and biomechanics. Clearly, we have much yet to learn about these demanding and existing forms of biathlon competitions.

## AUTHOR CONTRIBUTIONS

H-CH initiated the study. ML, MJ, and H-CH contributed similarly to literature research and writing, approved the final version to be published, and agreed to be accountable for all aspects of the work.

## REFERENCES

Andersson, E., Supej, M., Sandbakk, Ø., Sperlich, B., Stöggl, T., and Holmberg, H. C. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur. J. Appl. Physiol.* 110, 585–595. doi: 10.1007/s00421-010-1535-2

Bergh, U., and Forsberg, A. (2000). "Cross-country ski racing," in *Endurance in Sport*, 2nd Edn, eds R. J. Shephard and P. O. Åstrand (Oxford: Blackwell Publisher), 844–856. doi: 10.1002/9780470694930.ch57

Era, P., Konttinen, N., Mehto, P., Saarela, P., and Lyytinen, H. (1996). Postural stability and skilled performance–a study on top-level and naive rifle shooters. *J. Biomech.* 29, 301–306. doi: 10.1016/0021-9290(95)00066-6

Groslambert, A., Candau, R., Grappe, F., Dugue, B., and Rouillon, J. D. (2003). Effects of autogenic and imagery training on the shooting performance in biathlon. *Res. Q. Exerc. Sport* 74, 337–341. doi: 10.1080/02701367.2003.10609100

Groslambert, A., Candau, R., Hoffman, M. D., Bardy, B., and Rouillon, J. D. (1999). Validation of simple tests of biathlon shooting ability. *Int. J. Sports Med.* 20, 179–182. doi: 10.1055/s-1999-970286

Hegge, A. M., Bucher, E., Ettema, G., Faude, O., Holmberg, H. C., and Sandbakk, Ø. (2016). Gender differences in power production, energetic capacity and efficiency of elite crosscountry skiers during whole-body, upper-body, and arm poling. *Eur. J. Appl. Physiol.* 116, 291–300. doi: 10.1007/s00421-015-3281-y

Hoffman, M. D., Gilson, P. M., Westenburg, T. M., and Spencer, W. A. (1992). Biathlon shooting performance after exercise of different intensities. *Int. J. Sports. Med.* 13, 270–273. doi: 10.1055/s-2007-1021265

Hoffman, M. D., and Street, G. M. (1992). Characterization of the heart rate response during biathlon. *Int. J. Sports Med.* 13, 390–394. doi: 10.1055/s-2007-1021286

Holmberg, H. C. (2005). *The Physiology of Cross-Country Skiing : With Special Emphasis on the Role of the Upper Body*. Doctoral thesis, Karolinska Institutet, Solna.

Holmberg, H. C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scand. J. Med. Sci. Sports* 25(Suppl. 4), 100–109. doi: 10.1111/sms.12601

IBU (2017). *IBU Event and Competition Rules*. Salzburg: International Biathlon Union.

IBU (2018). *Datacenter*. Salzburg: International Biathlon Union.

Ihalainen, S., Laaksonen, M. S., Kuitunen, S., Leppavuori, A., Mikkola, J., Lindinger, S. J., et al. (2018). Technical determinants of biathlon standing shooting performance before and after race simulation. *Scand. J. Med. Sci. Sports* 28, 1700–1707. doi: 10.1111/sms.13072

Laaksonen, M. S., Ainegren, M., and Lisspers, J. (2011). Evidence of improved shooting precision in biathlon after 10 weeks of combined relaxation and specific shooting training. *Cogn. Behav. Ther.* 40, 237–250. doi: 10.1080/16506073.2011.616217

Laursen, P. B., and Jenkins, D. G. (2002). The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med.* 32, 53–73. doi: 10.2165/00007256-200232010-00003

Luchsinger, H., Kocbach, J., Ettema, G., and Sandbakk, Ø. (2018). Comparison of the effects of performance level and sex on sprint performance in the biathlon world cup. *Int. J. Sports Physiol. Perform.* 13, 360–366. doi: 10.1123/ijspp.2017-0112

Maier, T., Meister, D., Trösch, S., and Wehrlin, J. P. (2018). Predicting biathlon shooting performance using machine learning. *J. Sports Sci. Mar.* 22, 1–7. doi: 10.1080/02640414.2018.1455261

Niinimaa, V., and McAvoy, T. (1983). Influence of exercise on body sway in the standing rifle shooting position. *Can. J. Appl. Sport Sci.* 8, 30–33.

Nilsson, J. E., Holmberg, H. C., Tveit, P., and Hallen, J. (2004). Effects of 20-s and 180-s double poling interval training in cross-country skiers. *Eur. J. Appl. Physiol.* 92, 121–127. doi: 10.1007/s00421-004-1042-4

Rundell, K. W., and Szmedra, L. (1998). Energy cost of rifle carriage in biathlon skiing. *Med. Sci. Sports Exerc.* 30, 570–576. doi: 10.1097/00005768-199804000-00015

Sandbakk, Ø., Bucher Sandbakk, S., Supej, M., and Holmberg, H. C. (2014). The velocity and energy profiles of elite cross-country skiers executing downhill turns with different radii. *Int. J. Sports Physiol. Perform.* 9, 41–47. doi: 10.1123/IJSPP.2013-0383

Sandbakk, S. B., Supej, M., Sandbakk, Ø., and Holmberg, H. C. (2014). Downhill turn techniques and associated physical characteristics in cross-country skiers. *Scand. J. Med. Sci. Sports* 24, 708–716. doi: 10.1111/sms.12063

Sandbakk, Ø., Ettema, G., and Holmberg, H. C. (2012). The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. *Eur. J. Appl. Physiol.* 112, 2829–2838. doi: 10.1007/s00421-011-2261-0

Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sattlecker, G., Buchecker, M., Birklbauer, J., Müller, E., and Lindinger, S. (2013). "Effects of fatigue on shooting performance and biomechanical patterns in elite biathletes," in *Science and Skiing*, eds E. Müller, J. Kröll, and S. Lindinger (Aachen: Meyer & Meyer Verlag), 527–536.

Sattlecker, G., Buchecker, M., Gressenbauer, C., Müller, E., and Lindinger, S. J. (2017). Factors discriminating high from low score performance in biathlon shooting. *Int. J. Sports Physiol. Perform.* 12, 377–384. doi: 10.1123/ijspp.2016-0195

Sattlecker, G., Müller, E., and Lindinger, S. (2009). "Biomechanical factors of biathlon shooting in elite and youth athletes," in *Science and Skiing*, eds E. Müller, S. Lindinger, and T. Stöggl (Aachen: Meyer & Meyer Verlag), 641–646.

Skattebo, Ø., and Losnegard, T. (2018). Variability, predictability and race factors affecting performance in elite biathlon. *Int. J. Sports Physiol. Perform.* 13, 313–319. doi: 10.1123/ijspp.2017-0090

Smith, G. A. (1990). Biomechanics of cross-country skiing. *Sports Med.* 9, 273–285. doi: 10.2165/00007256-199009050-00003

Stöggl, T., Bishop, P., Höök, M., Willis, S., and Holmberg, H. C. (2015). Effect of carrying a rifle on physiology and biomechanical responses in biathletes. *Med. Sci. Sports Exerc.* 47, 617–624. doi: 10.1249/MSS.0000000000000438

Stöggl, T., and Müller, E. (2009). Kinematic determinants and physiological response of cross-country skiing at maximal speed. *Med. Sci. Sports Exerc.* 41, 1476–1487. doi: 10.1249/MSS.0b013e31819b0516

Stöggl, T., Müller, E., Ainegren, M., and Holmberg, H. C. (2011). General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand. J. Med. Sci. Sports* 21, 791–803. doi: 10.1111/j.1600-0838.2009.01078.x

Tønnessen, E., Haugen, T. A., Hem, E., Leirstein, S., and Seiler, S. (2015). Maximal aerobic capacity in the winter-Olympics endurance disciplines: Olympic-medal benchmarks for the time period 1990-2013. *Int. J. Sports Physiol. Perform.* 10, 835–839. doi: 10.1123/ijspp.2014-0431

Tønnessen, E., Sylta, O., Haugen, T. A., Hem, E., Svendsen, I. S., and Seiler, S. (2014). The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. *PLoS One* 9:e101796. doi: 10.1371/journal.pone.0101796

Vickers, J. N., and Williams, A. M. (2007). Performing under pressure: the effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *J. Mot. Behav.* 39, 381–394. doi: 10.3200/JMBR.39.5.381-394

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

CASE REPORT
published: 13 July 2018
doi: 10.3389/fphys.2018.00931

# The Long-Term Development of Training, Technical, and Physiological Characteristics of an Olympic Champion in Nordic Combined

*Vegard Rasdal[1], Frode Moen[1,2] and Øyvind Sandbakk[1]**

*[1] Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway, [2] Department of Education, Norwegian University of Science and Technology, Trondheim, Norway*

Nordic combined requires high technical skills and vertical impulse for the ski-jumping event and aerobic endurance, ski efficiency and finish-sprint abilities to succeed in the subsequent cross-country race. The main aim of this study was to investigate the development of training, technical, and physiological characteristics during the last four seasons preceding the Olympic Games in a Nordic Combined Champion [∼74 kg (63 kg lean-mass)]. During the first season of the 4-year cycle, the development of lower-body muscle-mass and vertical jump velocity was prioritized, after which the emphasis on developing the technical abilities were increased over the following three seasons. While maintaining his vertical velocity in countermovement jump at ∼3 m·s$^{-1}$, despite an increase of 7 kg overall body-mass, the participant improved his vertical velocity in sport-specific ski jump imitation with 0.31 m·s$^{-1}$ coincidentally with high technical focus, including use of systematic mental training to enhance skill acquisition, and an almost twofold increase of annual imitation jumps in the four-season cycle. Endurance training increased from 462 h·season$^{-1}$ in season one to 635 h·season$^{-1}$ in season three, which was mainly due to more low-intensity training. Thereafter, endurance training in the Olympic season was reduced by 12% and more focus was placed on quality of each session and sufficient recovery. The highest $\dot{V}O_{2peak}$ (5.36 L·min$^{-1}$ and 72.0 ml·kg$^{-1}$·min$^{-1}$) was measured in the third season and thereafter maintained, although competition results were further improved toward the Olympics. The amount of moderate- (31.9 ± 2.8 h·season$^{-1}$, 43.0 ± 3.9 sessions·season$^{-1}$) and high-intensity (28.3 ± 3.1 h·season$^{-1}$, 52.3 ± 2.7 sessions·season$^{-1}$) endurance training was stable throughout the four-season period, with >65% being performed as skiing or roller ski skating. Development of finish-sprint ability was an important strategy throughout the entire period, and both Olympic gold medals were won in a finish-sprint. Altogether, this study provides unique data from the four-season cycle of a two-time Olympic gold medal winner in Nordic Combined, where high amounts of strength/power and endurance training is successfully combined toward a peak in the Olympic season. This knowledge shows how the combination of long-term endurance and strength/power may be optimized, and generates new hypotheses to be tested in future research.

**Keywords: endurance training, high-intensity training, mental training, strength training, power, periodization, tapering, concurrent training**

OPEN ACCESS

**Edited by:**
*Gregoire P. Millet, Université de Lausanne, Switzerland*

**Reviewed by:**
*Jamie Stanley, South Australian Sports Institute, Australia*
*Urs Granacher, Universität Potsdam, Germany*

***Correspondence:**
*Øyvind Sandbakk*
*oyvind.sandbakk@ntnu.no*

**Specialty section:**
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

**Received:** *27 April 2018*
**Accepted:** *25 June 2018*
**Published:** *13 July 2018*

**Citation:**
*Rasdal V, Moen F and Sandbakk Ø (2018) The Long-Term Development of Training, Technical, and Physiological Characteristics of an Olympic Champion in Nordic Combined. Front. Physiol. 9:931. doi: 10.3389/fphys.2018.00931*

## INTRODUCTION

Nordic Combined (NC) is a challenging Olympic winter sport where the athletes compete in both a ski-jumping event and a cross-country race on the same day (Rasdal et al., 2017). Ski-jumping requires well developed technical abilities, flexibility, high vertical impulse and low body-mass (Schwameder, 2008; Muller, 2009; Sandbakk et al., 2016; Rasdal et al., 2017), in addition to mental awareness and toughness to successfully solve the different phases of a ski jump (i.e., in-run, take-off, transition to flight, flight, preparation for landing, landing). However, the take-off is widely considered most important (Schwameder, 2008; Virmavirta et al., 2009), and a recent study showed vertical velocity achieved in ski jump imitation together with body-mass to account for 70% of the variance in SJ performance in a world cup NC event (Rasdal et al., 2017).

The athletes' performance in the SJ event results in a proportional time penalty for the following 10-km cross-country skiing pursuit race in the skating style (Rasdal et al., 2017). The ~25-min cross-country race is performed in varied terrain, in which high aerobic capacity, skiing efficiency and finish-sprint ability is important for performance (Sandbakk et al., 2010; Sandbakk and Holmberg, 2014; Tønnessen et al., 2015; Rasdal et al., 2017).

While there are numerous athletic disciplines where a combination of both endurance and strength/power are required for successful performance, none are as extreme as NC. Hence, the simultaneous development of ski-jumping and cross-country capacity in NC athletes is challenging, and its extreme combination is under-explored. Although only ~50–60% of the ski-jumping and cross-country specialists' training is executed by NC athletes in each discipline, they differ only 10–17% in the various laboratory capacities (Sandbakk et al., 2016). Finally, the athlete need to develop mental abilities to optimize both the highly complex technical task in ski-jumping and the physical demanding cross-country event.

The main aim of this study was to investigate the development of training, technical, and physiological characteristics of a NC athlete during a four-season cycle prior to winning two Olympic gold medals at the 2014 Sochi Winter Olympics.

## MATERIALS AND METHODS

### Participant

The participant (born in 1991) specialized in NC in 2007 and progressively improved performance over the four-season cycle preceding the 2014 Winter Olympics in Sochi where he won two gold medals in NC. See **Table 1** for laboratory capacities in this period that constitutes his four competitive seasons in the World Cup.

The study was approved by the Norwegian Social Science Data Services (NSD), and the participant provided written informed consent to participate in the study.

### Laboratory Testing

General vertical jumps [i.e., countermovement (CMJ) and squat jumps (SQJ)] and sport specific imitation jumps (IMIT) were performed two to three times each season from 2011 to 2012 that was his first season on the national team. Test results from the general preparation phase (GP) was used for descriptive analysis. Equipment and procedures are previously described (Sandbakk et al., 2016; Tønnessen et al., 2016) and, in all jumps, maximum vertical velocity of the center of mass was used for further analysis.

Physiological testing on roller skis was done two to three times each season, and results from GP was used for descriptive analysis. Three or four 5-min submaximal stages to compare physiological response at 4 mmol·$L^{-1}$ blood lactate concentration, and an incremental maximal roller ski test to determine $\dot{V}O_{2peak}$ were performed. Equipment and procedures are previously described (Sandbakk et al., 2010, 2016) and, in all cases, respiratory variables (including determination of $\dot{V}O_{2peak}$) were calculated according to a previous study (Sandbakk et al., 2016).

One month after the 2014 Winter Olympics, the participant also performed DXA-measurement, from which lean-body-mass is reported.

### Training Monitoring and Systematization of Training Data

The participant recorded his day-to-day training in a digital diary[1] as previously described (Tønnessen et al., 2016), with all training sessions being systemized and analyzed in Microsoft Office Excel 2016 (Microsoft, Redmond, WA, United States). Endurance sessions were registered using the *modified session-goal approach* (Sylta et al., 2014) as low-intensity (LIT), moderate-intensity (MIT), and high-intensity (HIT) zones and further split into various types of session-categories within each zone, as previously described (Solli et al., 2017). In addition, an own class for recovery, warm-up, and cool-down was defined (WUP).

When speed training was integrated into endurance sessions, 2 min per sprint was registered as speed training. Non-endurance training, such as ski-jumping and strength/power sessions, were registered from the start to the finish of the specific part of the session, including recovery periods between sets. Dry land technique-training was reported as ski-jumping time, and is solely reported as the number of IMITs performed.

Training data are presented annually and divided into different periodization phases, based on key periodization models (Issurin, 2010; Tønnessen et al., 2016) that are slightly modified due to personal communication with the athlete and his coach; Phase 1 (GP1; June–August) and Phase 2 (GP2; September–October) of the General Preparatory Phase, Specific Preparatory Phase (SP; November–December), and Competition Phase (CP; January–March).

Furthermore, in-depth taper analysis of the 2013–2014 Olympic season, including weekly training data over the last 6 weeks and daily training content in the 14 days preceding

[1] www.olt-dagbok.net

**TABLE 1 |** Laboratory capacities determined during the ground preparation phase from 2010–2011 to 2013–2014, as well as immediately after the Olympic Games (Post) in an Olympic Nordic Combined Champion.

| | | 2010–2011 | 2011–2012 | 2012–2013 | 2013–2014 | Post |
|---|---|---|---|---|---|---|
| Body-mass | (kg) | 66.5 | 73.2 | 74.5 | 73.8 | 75.3 |
| **Vertical jump velocity** | | | | | | |
| $Vv_{SQJ}$ | (m·s$^{-1}$) | | 2.91 | 2.94 | 2.96 | 3.05 |
| $Vv_{CMJ}$ | (m·s$^{-1}$) | | 3.04 | 3.05 | 3.13 | 3.10 |
| $Vv_{IMIT}$ | (m·s$^{-1}$) | | 2.14 | 2.37 | 2.34 | 2.45 |
| **Maximal aerobic power** | | | | | | |
| $\dot{V}O_{2peak}$ | (ml·kg$^{-1}$·min$^{-1}$) | 68.8 | 69.3 | 72.0 | 71.0 | 72.1 |
| | (L·min$^{-1}$) | 4.58 | 5.07 | 5.36 | 5.24 | 5.43 |
| **Responses at 4 mmol·L$^{-1}$ BLa** | | | | | | |
| $\dot{V}O_2$ | (L·min$^{-1}$) | 3.51 | 4.01 | 4.36 | 4.21 | 4.31 |
| | (ml·kg$^{-1}$·min$^{-1}$) | 52.8 | 54.8 | 58.3 | 57.0 | 57.3 |
| | (% peak) | 77 | 79 | 81 | 80 | 79 |

**The test with the highest performance level in the period June–October was selected for analysis in the seasons 2010–2011 to 2013–2014. To better reflect the performance level required for the Olympics, also tests immediately post 2013–2014 season was selected (post). $Vv_{SQJ}$, maximum achieved vertical velocity in squat jump; $Vv_{CMJ}$, maximum achieved vertical velocity in countermovement jump; $Vv_{IMIT}$, maximum achieved vertical velocity in imitation jump; $\dot{V}O_{2peak}$, peak oxygen uptake from incremental test to exhaustion; BLa, blood lactate concentration; $\dot{V}O_2$, oxygen uptake.*

winning Olympic gold medal, are presented. Of the 6 weeks, the final 2 weeks before winning the first gold medal was defined as peaking phase and the preceding 4 weeks as pre-peaking phase.

## Qualitative Analyses

To track missing data, ensure compliance with the training diary commentaries, and to verify the intensity of different training sessions, two interviews with the participant were conducted during the data-analysis phase of this study. Also two interviews with the participant's main coach was conducted to gather a qualitative representation of determining factors for the participant's success. In order to gain an overall understanding of the development of ski-jumping, we performed multi-disciplinary workshops with the authors of this study, his ski-jumping-coach and the mental coach to analyze training logs, tests and competition results, as well as videos and focus during the mental training throughout these seasons.

# RESULTS

The participant recorded 804, 824, 1,008, and 950 training hours·season$^{-1}$ from 2010–2011 to 2013–2014, distributed across 472, 519, 582, and 585 training sessions. The detailed development of the various training components is depicted in **Figure 1**. The participant gained ∼7 kg of body-mass from 66.5 kg in 2010–2011 to 73.2 kg in 2011–2012, and thereafter stabilized at ∼74 kg (**Table 1**). Lean body-mass was measured shortly after the Olympics to be 63.0 kg.

## Non-endurance

Whereas the amount of general strength/power training varied as a sine wave between 90 and 140 h·season$^{-1}$, the amount of ski-jump specific strength/power training and the number of IMITs increased steadily each season (**Figures 1A,B**). Coincidentally, the vertical jump velocity in SQJ and CMJ varied less than 5%, whereas the vertical velocity in IMIT showed a 14.5% increase from 2.14 to 2.45 m·s$^{-1}$ in the same period (**Table 2**). The participant reported that the compilation of strength/power sessions in 2010–2011 season was focused toward building lower-body muscle-mass and maximal strength, whereas more high-velocity exercises in ski-jump-specific movement patterns were emphasized from 2011 to 2012. High focus was put on improving ankle-flexibility and hip/core control in the ski-jump-specific movement, and at the same time technically aim to (1) reduce fluctuations of the center of mass in relation to the center of pressure in the in-run and (2) have the center of mass placed vertically above the center of pressure (i.e., lower lever-arm) during the take-off phase.

## Endurance

The participant increased his aerobic capacity by 0.78 L·min$^{-1}$ from 2010–2011 to 2012–2013 season, whereas his body-mass-normalized $\dot{V}O_{2peak}$ was relatively stable across the entire period (**Table 2**). $\dot{V}O_2$ at 4 mmol·L$^{-1}$ blood lactate concentration increased from 77% in 2010–2011 to >80% of $\dot{V}O_{2peak}$ (**Table 2**).

The participant had a polarized periodization in all seasons, with the overall variation in endurance training volume mainly manipulated by LIT (**Figure 1C**). The amount of MIT and HIT was almost identical in all four seasons, except from a 22% decrease in the amount of MIT from 2012–2013 to 2013–2014 (**Figure 1C**). The main type of intervals for MIT and HIT sessions were in the range of 6–15 min and 3–5 min, respectively (**Table 2**). For all intensities, the average session duration was shorter in SP and CP compared to GP1 and GP2 (**Table 2**). The participant included sprints in nearly all LIT sessions on roller skis and skis, while sprints at the end of some of the MIT/HIT sessions stressed the ability to maintain a well-executed technique when fatigued. Sprint training was included 101, 114, 126, and 129 times·season$^{-1}$ in the respective seasons from 2010–2011 to 2013–2014, and was usually performed as approximately ∼5 sprints of 6–8 s.

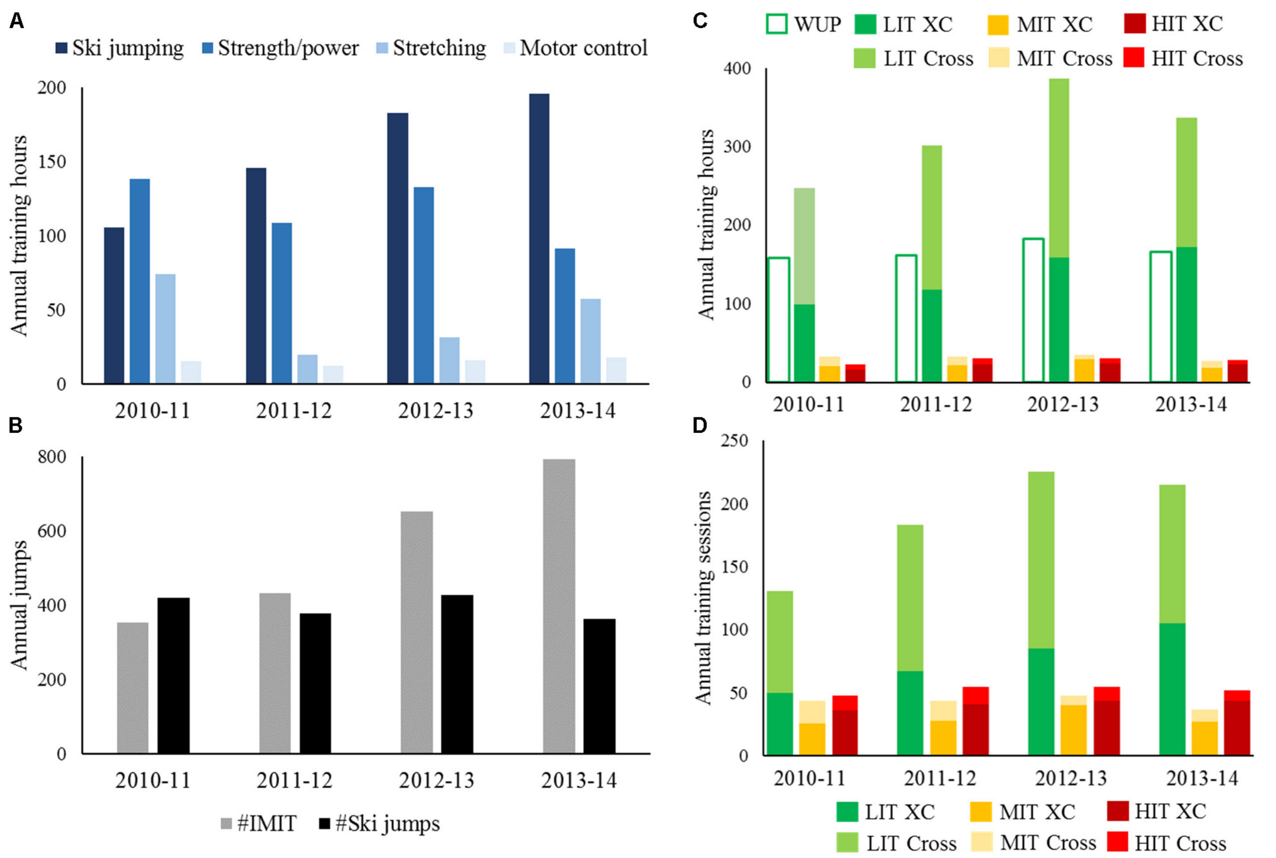


**FIGURE 1 |** Annual non-endurance training hours **(A)** and number of jumps **(B)**, as well as annual endurance training hours **(C)** and sessions **(D)** from the seasons 2010–2011 to 2013–2014 in an Olympic Champion in Nordic Combined. IMIT, dry-land imitation jump of a ski jump; WUP, time spent for warm-up, cool-down, and recovery; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training; XC, cross-country session employing skating technique; cross, endurance session not employing cross-country skating technique.

The amount of endurance training was distributed equally between specific and unspecific training modes (i.e., 45, 44, 47, and 54% cross-country skating in the respective seasons from 2010–2011 to 2013–2014). More than two-thirds of MIT and HIT was performed on skis or roller-skis in all seasons, whereas for LIT 50–60% cross training was performed (**Figures 1C,D**).

Although some training camps throughout the cycle was at altitude > 1,500 m above sea level, no systematic altitude training was performed.

## Tapering

The weekly distribution of training during the final 6 weeks and daily description of the final 2 weeks prior to winning the first gold medal is presented in **Tables 3A,B**. Overall, the training load and distribution between endurance and non-endurance training was similar for all six preceding weeks, except from week −4 and −2 (**Table 3A**), in which total training volume was ∼25% lower in both weeks compared to the other four. The reduction of training load in week −2 was mainly a result of traveling, whereas the reduction in week −4 was a consequence of no ski jumping. The weekly amount of endurance training in week −4 was two-thirds higher compared to the other 5 weeks. From pre-peaking phase to peaking phase, the overall training volume was reduced by 8% whereas endurance training volume was reduced by 25%.

## Qualitative Assessment

The participant was involved in multiple of sport disciplines until the start of high-school, when he decided to specialize in NC at the age of 16. Since then, he had a close and well-functioning working-alliance with the same, high-level coach, with all training directed toward sport-specific goals. He was also part of a well-functioning training group that included two of the world's best NC athletes throughout the entire period. Here, regular team processes and daily training provided the possibility to develop and train at the highest level. During this period, he used mental training systematically to improve ski-jump-technique by, e.g., developing an automatized awareness of in-run position and balance and to optimize the take-off dynamics, especially in stressful situations in the hill. Although the participant quickly improved technical skills in dry-land training, the ability to translate this to the ski-jumping hill was more gradual. Hence, his ability to perform on top in important competitions were gradually improved and optimized toward the Olympics.

**TABLE 2 |** Mean session duration and number of monthly training sessions of the different endurance session categories in each intensity zone across seasons and periodization phases from 2010–2011 to 2013–2014 in an Olympic Nordic Combined champion.

| | Per season | | | | Mean ± SD of the four-season cycle | | | | 2013–2014 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2010–2011 | 2011–2012 | 2012–2013 | 2013–2014 | GP1 | GP2 | SP | CP | GP1 | GP2 | SP | CP |
| **Mean session duration** | | | | | | | | | | | | |
| LIT (hrs·sess$^{-1}$) | 1.9 | 1.6 | 1.7 | 1.6 | 1.7 ± 0.2 | 1.7 ± 0.1 | 1.6 ± 0.1 | 1.5 ± 0.1 | 1.6 | 1.6 | 1.4 | 1.3 |
| MIT (min·sess$^{-1}$) | 44.1 | 45.2 | 44.2 | 44.5 | 51.2 ± 2.3 | 48.1 ± 6.1 | 43.4 ± 4.3 | 32.2 ± 2.3 | 53.1 | 54.6 | 38.5 | 29.6 |
| HIT (min·sess$^{-1}$) | 28.9 | 34.2 | 33.5 | 32.8 | 35.7 ± 3.5 | 41.3 ± 3.9 | 29.8 ± 3.6 | 27.7 ± 1.0 | 36.9 | 39.5 | 33.4 | 27.8 |
| **Categories LIT** | | | | | | | | | | | | |
| <50 min (sess·mth$^{-1}$) | 0.2 | 2.3 | 2.2 | 1.5 | 1.6 ± 1.2 | 1.5 ± 0.9 | 2.0 ± 1.3 | 1.8 ± 0.8 | 1.0 | 1.5 | 2.5 | 1.7 |
| 50–90 min (sess·mth$^{-1}$) | 1.8 | 3.6 | 4.1 | 6.1 | 4.2 ± 1.7 | 2.6 ± 1.2 | 3.7 ± 1.9 | 5.3 ± 2.3 | 6.5 | 3.4 | 6.9 | 7.7 |
| 90–120 min (sess·mth$^{-1}$) | 4.9 | 3.0 | 5.3 | 5.2 | 6.4 ± 2.4 | 5.7 ± 1.1 | 5.0 ± 1.2 | 2.3 ± 1.4 | 9.5 | 6.9 | 3.4 | 2.0 |
| >120 min (sess·mth$^{-1}$) | 3.8 | 6.2 | 6.8 | 4.9 | 5.0 ± 1.3 | 6.5 ± 2.9 | 5.3 ± 0.9 | 3.7 ± 1.1 | 3.6 | 5.4 | 5.9 | 3.3 |
| **Categories MIT** | | | | | | | | | | | | |
| Continuous (sess·mth$^{-1}$) | 0.1 | 0.2 | 0.1 | 0.3 | 0.2 ± 0.2 | 0.2 ± 0.2 | 0.1 ± 0.2 | 0.0 ± 0.0 | 0.3 | 0.5 | 0.5 | 0.0 |
| <8 min (sess·mth$^{-1}$) | 1.1 | 1.1 | 1.5 | 0.7 | 0.7 ± 0.3 | 1.0 ± 0.6 | 1.6 ± 0.4 | 1.7 ± 0.6 | 0.7 | 0.5 | 1.5 | 1.0 |
| 8–15 min (sess·mth$^{-1}$) | 1.1 | 0.7 | 1.5 | 1.1 | 1.6 ± 0.3 | 1.4 ± 0.2 | 0.9 ± 0.4 | 0.8 ± 0.4 | 2.0 | 1.0 | 1.0 | 0.7 |
| >15 min (sess·mth$^{-1}$) | 0.0 | 0.3 | 0.0 | 0.1 | 0.2 ± 0.3 | 0.1 ± 0.2 | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.0 | 0.5 | 0.0 | 0.0 |
| Unspecified (sess·mth$^{-1}$) | 1.4 | 1.2 | 0.9 | 0.8 | 2.0 ± 0.8 | 1.2 ± 0.5 | 0.5 ± 0.6 | 0.7 ± 0.6 | 1.0 | 1.0 | 0.0 | 0.7 |
| **Categories HIT** | | | | | | | | | | | | |
| Continuous (sess·mth$^{-1}$) | 0.3 | 2.5 | 2.5 | 2.4 | 1.5 ± 0.4 | 1.4 ± 0.4 | 3.1 ± 0.7 | 5.2 ± 0.2 | 2.0 | 1.5 | 2.0 | 5.0 |
| <3 min (sess·mth$^{-1}$) | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 ± 0.0 | 0.1 ± 0.2 | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3–5 min (sess·mth$^{-1}$) | 0.5 | 1.1 | 1.2 | 1.2 | 0.7 ± 0.6 | 1.4 ± 0.7 | 1.0 ± 0.6 | 1.2 ± 0.2 | 0.7 | 2.5 | 1.0 | 1.0 |
| >5 min (sess·mth$^{-1}$) | 0.1 | 0.3 | 0.2 | 0.3 | 0.2 ± 0.4 | 1.0 ± 0.8 | 0.1 ± 0.2 | 0.0 ± 0.0 | 0.0 | 1.5 | 0.5 | 0.0 |
| Unspecified (sess·mth$^{-1}$) | 0.4 | 0.5 | 0.6 | 0.3 | 1.1 ± 0.4 | 0.2 ± 0.2 | 0.2 ± 0.2 | 0.2 ± 0.1 | 1.0 | 0.0 | 0.0 | 0.3 |

*GP, general preparatory phase; SP, specific preparatory phase; CP, competition phase; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training.*

**TABLE 3 |** Weekly training content during the final 6 weeks **(A)** prior to winning two individual gold medals in the 2014 Sochi Winter Olympics, with detailed description of the training performed during the last 14 days **(B)** in an Olympic Nordic Combined champion.

| **A** | **Weekly training content during the final 6 weeks prior to gold medal** | | | | | |
|---|---|---|---|---|---|---|
| **Week** | **Non-endurance hours (sessions)** | ***SJ hours (sessions)*** | **Endurance hours (sessions)** | ***XC MIT hours (sessions)*** | ***XC HIT hours (sessions)*** | **Total hours (sessions)** |
| −6 | 10.3 (6) | *7.3 (5)* | 8.7 (6) | *0.0 (0)* | *0.8 (2)* | 18.9 (12) Two competitions |
| −5 | 10.6 (6) | *8.2 (5)* | 10.2 (7) | *0.0 (0)* | *1.5 (3)* | 20.8 (13) Three competitions |
| −4 | 1.8 (3) | *0.0 (0)* | 14.8 (8) | *0.8 (1)* | *0.0 (0)* | 16.7 (11) |
| −3 | 11.4 (9) | *6.3 (5)* | 8.9 (5) | *0.0 (0)* | *1.2 (2)* | 20.4 (14) |
| −2 | 7.1 (4) | *3.9 (3)* | 7.9 (5) | *0.0 (0)* | *0.8 (2)* | 15.0 (9) |
| −1 | 11.5 (5) | *6.7 (4)* | 9.1 (7) | *0.7 (2)* | *0.0 (0)* | 20.6 (12) |
| 0 | *Individual gold medal, Olympic Winter Games 2014* | | | | | |

| **B** | **Daily training content during the last 2 weeks prior to gold medal** | |
|---|---|---|
| **Day** | **AM** | **PM** |
| −14 | *Rest day* | |
| −13 | 1.5 h strength/power* | 1.5 h LIT with 4 × 6–8 s sprints, XC |
| −12 | 0.75 h LIT, running + 0.25 h flexibility | *Travel* |
| −11 | *Travel day* | |
| −10 | 1.5 h LIT, running | 1 h dry land technique session |
| −9 | 2 h SJ[c]* | 5 × 3 min HIT[d], XC |
| −8 | 2 h SJ[c]* | 1 h LIT, XC |
| −7 | 2 h SJ[c]* | 1 h LIT, XC |
| −6 | 1.5 h strength/power* | 0.3 h LIT, running + 0.3 h flexibility |
| −5 | 0.5 h LIT, running | 1.25 h LIT, running |
| −4 | 0.3 h LIT, running + 0.7 h flexibility | 0.25 h flexibility |
| −3 | 2.5 h SJ[c]* | 5 × 7 min MIT[d], XC |
| −2 | 2.5 h SJ[c]* | 1.25 h LIT, XC |
| −1 | 2 h SJ[c]* | 1 h LIT with 3 × 8 s sprints, XC |
| 0 | *Individual gold medal, Olympic Winter Games 2014* | |

*[c]Official ski jumping training in relation to competition. [d]MIT and HIT sessions normally included 20–40 min of LIT as warm-up and 15–30 min LIT as cool-down. SJ, ski jumping session; XC, cross-country skiing employing skating technique; technique session, exercises designed to imitate ski jumping on dry land; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training. *Time of non-endurance sessions is from start to the end of session, including warm-up and recovery between sets.*

Sequencing of sessions throughout the seasons was based on the competition format of the sport, i.e., with strength/power and ski-jump sessions performed early in the day and endurance sessions in the afternoon with 2–4 h in between (when performed on the same day). For seasonal periodization, the GP1 contained relatively more focus on strength/power and high load of endurance training, whereas the focus on key development sessions (i.e., SJ sessions, and intervals on roller skis/skis) increased from GP2 toward CP.

## DISCUSSION

The present study investigated the development of training, technical, and physiological characteristics during the last four seasons preceding the Olympic Winter Games in an Olympic NC Champion. After an initial focus of increasing lower-body muscle-mass and vertical jump velocity, the participant had a greater emphasis on technical sessions over the following three seasons. At the same time, the athlete was included in a group of world-class NC athletes and systematic mental training to enhance skill acquisition was included. After a progressive increase of endurance training over the first three seasons, this was reduced by 12% in the Olympic season. While maintaining his CMJ vertical jump velocity at ∼3 $m{\cdot}s^{-1}$, despite an increase of 7 kg overall body-mass, the participant improved his vertical jump velocity of sport-specific IMITs with 0.31 $m{\cdot}s^{-1}$ and $\dot{V}O_{2peak}$ with ∼0.8 $L{\cdot}min^{-1}$ coincidentally with an almost twofold increase of annual IMITs and an increase of ∼200 annual endurance hours in the four-season cycle. An emphasis on improving finish-sprint ability in cross-country skiing was present in all seasons, a determining factor since both Olympic gold medals were won in the finish-sprint. Tapering toward the Olympic included a 25% reduction in endurance training volume and an 8% increase in non-endurance training from pre-peaking to peaking phase.

## Non-endurance

Already in 2011, the athlete had reached a world-class vertical jump velocity of ~2.9 $m \cdot s^{-1}$ in CMJ and SQJ (Tønnessen et al., 2016; Rasdal et al., 2017). This was likely a consequence of the strength/power focus in the 2010–2011-season, compiled toward muscle hypertrophy and maximal lower-body strength. Thereafter, strength/power sessions were focused more toward high-velocity exercises with ski-jump-specific movement pattern. This shift of exercise content, with more specificity when the level of strength was sufficient, also allowed for maintaining his jump capacity along with the large increase of endurance training that often induce negative influence on power development (Nader, 2006; Wilson et al., 2012; Baar, 2014). Coinciding the increase in the number of IMITs, ski-jump-specific vertical jump velocity improved with ~15%, indicating that the execution of this technical skill was not negatively influenced by concurrent endurance training. Overall, it may be beneficial for NC athletes to improve strength and vertical impulse at an early phase, followed by a greater focus on high-velocity exercises in a ski-jump-specific movement pattern when increasing the annual endurance load.

With an in-run speed of 85–95 $km \cdot h^{-1}$ and less than 0.35 s to complete the take-off (Muller, 2009), the athlete relies on an automated and technically optimized take-off pattern. Improved ankle-flexibility and hip/core control enabled our participant to solve the task (see description in the "Results" section) well during dry-land training and testing already early in the Olympic cycle, but it required longer time to transfer this skill to ski-jumping in the hill. Here, systematic mental training to enhance skill acquisition supported the technique training, which was likely a crucial factor for the participant's success at the Olympic Games. Since we do not have good quantitative measurement of these aspects of the ski-jump technique, future studies should strive to develop and validate such measurements both for laboratory and field testing.

## Endurance

The polarized intensity model and overall endurance volume of ~560 $h \cdot season^{-1}$ in the Olympic season is similar to earlier reported values from successful seasons in NC athletes (Tønnessen et al., 2016). The amount of endurance training was, however, increased by an average of 87 $h \cdot season^{-1}$ over the initial three seasons, having a peak of 635 $h \cdot season^{-1}$, followed by a reduction in the Olympic season. While this is clearly lower than top-level cross-country skiers who progress their training up to ~8–900 annual endurance training hours (Sandbakk and Holmberg, 2014; Solli et al., 2017), NC athletes train more hours than cross-country skier when including their ski-jumping training (Sandbakk et al., 2016). However, the annual training cannot be directly compared between the two winter sports as the different loads of cross-country versus ski-jumping training and the subsequent risk of overreaching must be considered differently. Nevertheless, the current study indicates that a progressive increase in endurance training load during an Olympic cycle followed by a reduction in the peak season may be beneficial for overall long-term development in NC.

The annual increase in endurance training load until the 2012–2013 season, coupled with 7 kg increase in body-mass, led to a gradual increase of $\dot{V}O_{2peak}$ up to 5.36 $L \cdot min^{-1}$ and 72.0 $ml \cdot kg^{-1} \cdot min^{-1}$, which is within previously reported benchmark values in world-class NC athletes (Tønnessen et al., 2015; Sandbakk et al., 2016; Rasdal et al., 2017). In the 2012–2013 season, ~80% of MIT and HIT sessions (compared to 70% before) was performed in skating, which most likely contributed to the increased utilization of $\dot{V}O_{2peak}$ at 4 $mmol \cdot L^{-1}$ of blood lactate, as well as a further increase in roller ski $\dot{V}O_{2peak}$ that season. The subsequent reduction of endurance training load from 2012–2013 to 2013–2014 was partly compensated by more skating also in the LIT zone, and might have led to maintenance of endurance capacity in the Olympic season. However, the lower endurance load may have reduced overall fatigue and thus improved the quality in the non-endurance sessions as well, enabling a further development of the vertical jump velocity in the Olympic season (measured after the 2013–2014 season). This may overall suggest that the reduction was beneficial for development of ski-jumping performance, and thus, the overall NC performance.

## Tapering

The tapering strategy of 25% reduction in endurance training load from the pre-peaking phase to the peaking phase is somewhat higher than previously found in successful cross-country skiers and biathletes (Tønnessen et al., 2014; Solli et al., 2017), and is more than the 20% reduction recommended for achieving a tapering effect (Bosquet et al., 2007). Overall training load, however, was decreased by only 8% as non-endurance load was increased from pre-peaking to the peaking phase. Tønnessen et al. (2014) speculated in their study that the lower reduction in training volume found among elite cross-country skiers compared to what is suggested by the literature could be ideal in sports with a dense competition schedule. However, NC athletes are also dependent on ski-jumping facilities to be able to jump, and thus logistics govern much of their training plan. This may also explain the three-phase tapering format in the participants' endurance training load, where a 45% increase from week −5 to −4 was coupled with no ski-jumping in week −4. How to taper for an optimal ski-jumping performance has not previously been researched, and its delicate interplay with endurance training to achieve optimal NC performance sorely needs to be further investigated in future group studies.

# CONCLUSION

Our study provides unique data from the four-season cycle of a two-time Olympic gold medal winner in NC. The participant focused on increasing lower-body muscle strength and vertical jump impulse early in the cycle, followed by increased emphasis on technical ski-jumping sessions and inclusion in a high-level training group. Here, improved ankle-flexibility and hip/core control, together with systematic mental training, gradually enabled our participant to solve the technical task in the hill. A progressive increase of low-intensity endurance training over the three first seasons was followed by reduced endurance training volume, but with a higher degree of specific training in the Olympic season to enable greater quality in each session and to trigger surplus in developing ski-jumping performance. Improving finish-sprint ability was emphasized in all seasons, and was a determining factor for winning both Olympic gold medals. Peaking toward the Olympics included an overload of endurance training in the pre-peaking phase before a 25% reduction in the peaking phase. Consequently, non-endurance training was increased from pre-peaking to the peaking phase and the overall training was not reduced more than 8%. Altogether, this study provides insight into how the combination of long-term endurance and strength/power training may be optimized, and generates new hypotheses to be tested in future group studies. In particular, detailed description and analysis of non-endurance training is lacking in the majority of studies on concurrent and strength/power sports. We thus encourage future studies to investigate the training load of strength/power, both as an isolated stimuli, and concurrently to endurance training.

## AUTHOR CONTRIBUTIONS

VR, FM, and ØS designed the study, contributed to interpretation of the results, and contributed to the final manuscript. VR performed the data collection. VR and ØS performed the data and statistical-analysis and wrote the draft manuscript.

## ACKNOWLEDGMENTS

The authors sincerely thank the participant and his coaches for their valuable cooperation and participation in this study.

## REFERENCES

Baar, K. (2014). Using molecular biology to maximize concurrent training. *Sports Med.* 44(Suppl. 2), S117–S125. doi: 10.1007/s40279-014-0252-0

Bosquet, L., Montpetit, J., Arvisais, D., and Mujika, I. (2007). Effects of tapering on performance: a meta-analysis. *Med. Sci. Sports Exerc.* 39, 1358–1365. doi: 10.1249/mss.0b013e31806010e0

Issurin, V. B. (2010). New horizons for the methodology and physiology of training periodization. *Sports Med.* 40, 189–206. doi: 10.2165/11319770-000000000-00000

Muller, W. (2009). Determinants of ski-jump performance and implications for health, safety and fairness. *Sports Med.* 39, 85–106. doi: 10.2165/00007256-200939020-00001

Nader, G. A. (2006). Concurrent strength and endurance training: from molecules to man. *Med. Sci. Sports Exerc.* 38, 1965–1970. doi: 10.1249/01.mss.0000233795.39282.33

Rasdal, V., Fudel, R., Kocbach, J., Moen, F., Ettema, G., and Sandbakk, O. (2017). Association between laboratory capacities and world-cup performance in Nordic combined. *PLoS One* 12:e0180388. doi: 10.1371/journal.pone.0180388

Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sandbakk, Ø., Holmberg, H. C., Leirdal, S., and Ettema, G. (2010). Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur. J. Appl. Physiol.* 109, 473–481. doi: 10.1007/s00421-010-1372-3

Sandbakk, Ø., Rasdal, V., Braaten, S., Moen, F., and Ettema, G. (2016). How do world-class nordic combined athletes differ from specialized cross-country skiers and ski jumpers in sport-specific capacity and training characteristics? *Int. J. Sports Physiol. Perform.* 11, 899–906. doi: 10.1123/ijspp.2015-0285 doi: 10.1123/ijspp.2015-0285

Schwameder, H. (2008). Biomechanics research in ski jumping, 1991-2006. *Sports Biomech.* 7, 114–136. doi: 10.1080/14763140701687560

Solli, G. S., Tonnessen, E., and Sandbakk, O. (2017). The training characteristics of the world's most successful female cross-country skier. *Front. Physiol.* 8:1069. doi: 10.3389/fphys.2017.01069

Sylta, O., Tonnessen, E., and Seiler, S. (2014). From heart-rate data to training quantification: a comparison of 3 methods of training-intensity analysis. *Int. J. Sports Physiol. Perform.* 9, 100–107. doi: 10.1123/IJSPP.2013-0298

Tønnessen, E., Haugen, T. A., Hem, E., Leirstein, S., and Seiler, S. (2015). Maximal aerobic capacity in the winter-Olympics endurance disciplines: olympic-medal benchmarks for the time period 1990-2013. *Int. J. Sports Physiol. Perform.* 10, 835–839. doi: 10.1123/ijspp.2014-0431

Tønnessen, E., Rasdal, V., Svendsen, I. S., Haugen, T. A., Hem, E., and Sandbakk, Ø. (2016). Concurrent development of endurance capacity and explosiveness: training characteristics of world-class nordic-combined athletes. *Int. J. Sports Physiol. Perform.* 11, 643–651. doi: 10.1123/ijspp.2015-0309

Tønnessen, E., Sylta, Ø., Haugen, T. A., Hem, E., Svendsen, I. S., and Seiler, S. (2014). The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. *PLoS One* 9:e101796. doi: 10.1371/journal.pone.0101796

Virmavirta, M., Isolehto, J., Komi, P., Schwameder, H., Pigozzi, F., and Massazza, G. (2009). Take-off analysis of the olympic ski jumping competition (HS-106m). *J. Biomech.* 42, 1095–1101. doi: 10.1016/j.jbiomech.2009.02.026

Wilson, J. M., Marin, P. J., Rhea, M. R., Wilson, S. M., Loenneke, J. P., and Anderson, J. C. (2012). Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J. Strength Cond. Res.* 26, 2293–2307. doi: 10.1519/JSC.0b013e31823a3e2d

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

ORIGINAL RESEARCH
published: 31 July 2018
doi: 10.3389/fphys.2018.01036

# Combining Chronic Ischemic Preconditioning and Inspiratory Muscle Warm-Up to Enhance On-Ice Time-Trial Performance in Elite Speed Skaters

*Philippe Richard and François Billaut**

*Département de kinésiologie, Université Laval, Quebec, QC, Canada*

OPEN ACCESS

**Edited by:**
Gregoire P. Millet,
Université de Lausanne, Switzerland

**Reviewed by:**
Giovanni Messina,
University of Foggia, Italy
Gustavo R. da Mota,
Universidade Federal do Triângulo Mineiro, Brazil

***Correspondence:**
François Billaut
francois.billaut@kin.ulaval.ca

**Specialty section:**
This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology

**Received:** 17 February 2018
**Accepted:** 12 July 2018
**Published:** 31 July 2018

**Citation:**
Richard P and Billaut F (2018) Combining Chronic Ischemic Preconditioning and Inspiratory Muscle Warm-Up to Enhance On-Ice Time-Trial Performance in Elite Speed Skaters. Front. Physiol. 9:1036. doi: 10.3389/fphys.2018.01036

Elite athletes in varied sports typically combine ergogenic strategies in the hope of enhancing physiological responses and competitive performance, but the scientific evidence for such practices is very scarce. The peculiar characteristics of speed skating contribute to impede blood flow and exacerbate deoxygenation in the lower limbs (especially the right leg). We investigated whether combining preconditioning strategies could modify muscular oxygenation and improve performance in that sport. Using a randomized, single-blind, placebo-controlled, crossover design, seven male elite long-track speed skaters performed on-ice 600-m time trials, preceded by either a combination of preconditioning strategies (COMBO) or a placebo condition (SHAM). COMBO involved performing remote ischemic preconditioning (RIPC) of the upper limbs (3 × 5-min compression at 180 mmHg and 5-min reperfusion) over 3 days (including an acute treatment before trials), with the addition of an inspiratory muscle warm-up [IMW: 2 × 30 inspirations at 40% maximal inspiratory pressure (MIP)] on the day of testing. SHAM followed the same protocol with lower intensities (10 mmHg for RIPC and 15% MIP). Changes in tissue saturation index (TSI), oxyhemoglobin–oxymyoglobin ([$O_2$HbMb]), deoxyhemoglobin–deoxymyoglobin ([HHbMb]), and total hemoglobin–myoglobin ([THbMb]) in the right vastus lateralis muscle were monitored by near-infrared spectroscopy (NIRS). Differences between COMBO and SHAM were analyzed using Cohen's effect size (ES) and magnitude-based inferences. Compared with SHAM, COMBO had no worthwhile effect on performance time while mean Δ[HHbMb] (2.7%, ES 0.48; −0.07, 1.03) and peak Δ[HHbMb] (1.8%, ES 0.23; −0.10, 0.57) were respectively *likely* and *possibly* higher in the last section of the race. These results indicate that combining ischemic preconditioning and IMW has no practical ergogenic impact on 600-m speed-skating performance in elite skaters. The low-sitting position in this sport might render difficult enhancing these physiological responses.

**Keywords: warm up, chronic ischemic preconditioning, high-level athletes, muscle oxygen extraction, blood volume, sprint**

## INTRODUCTION

Elite speed skaters adopt a crouched position that is both aerodynamically and biomechanically favorable to performance (Noordhof et al., 2014). However, the combination of this low-sitting position, the isometric gliding phase and high intramuscular forces results in impeded blood flow to working muscles (Konings et al., 2015). Near-infrared spectroscopy (NIRS) studies further demonstrated that a low-skating position during in-line speed skating is associated with an accentuated deoxygenation when compared to an upper-skating position (Rundell et al., 1997). Comparison of oxygenation patterns in short- vs. long-track speed skating demonstrates that the former discipline leads to a more severe muscle deoxygenation (Hettinga et al., 2016). Moreover, higher perceived fatigue and slower recovery are reported two and four hours after short- vs. long-track time trials (Hettinga et al., 2016), suggesting that a greater deoxygenation in active muscles may negatively influence muscle recovery processes. Importantly, blood flow occlusion and tissue deoxygenation also occur during the gliding and push-off phases in long-track speed skating (Hettinga et al., 2016), thereby implicating physiological drawbacks, such as accentuated local hypoxic stress that may hasten peripheral fatigue development (Konings et al., 2015). The exact impact of the deoxygenation severity during speed-skating performance is however not clearly understood.

In order to optimize energy metabolism and with the ultimate goal of achieving maximal performance, elite athletes of different sports adopt several preconditioning techniques (Kilduff et al., 2013), priming exercises (Bailey et al., 2009) and warm-up strategies (McGowan et al., 2015). Although some of these protocols were found to modify oxygenation and improve performance, very few of these techniques were investigated on elite speed skaters during a specific performance task. Furthermore, data on the impact of a combination of techniques are very scarce in the literature.

In various sports and research settings, remote ischemic preconditioning (RIPC) was found to enhance performance [time to task failure (Barbosa et al., 2015; Kido et al., 2015; Tanaka et al., 2016), peak and mean power output (Patterson et al., 2015), maximal concentric force (Paradis-Deschênes et al., 2016)] concomitantly with an altered deoxygenation [attenuated (Kido et al., 2015; Patterson et al., 2015), accentuated (Barbosa et al., 2015; Paradis-Deschênes et al., 2016), and accelerated dynamics (Kido et al., 2015; Tanaka et al., 2016)]. These data highlight the equivocal relationship between oxygenation alterations and performance. Interestingly, our research group investigated the effects of RIPC on a 1000-m speed-skating race. This technique did not enhance performance, but was associated with an accentuated deoxygenation in sprint-specialized speed-skaters (Richard and Billaut, 2018). Considering the high ischemic stress associated with speed-skating itself and the fact that elite athletes present a narrower window of adaptation compared to less trained individuals (Marocolo et al., 2016a), we reasoned that a chronic RIPC stimulation (Foster et al., 2014) could represent a more effective strategy to modify acute physiological response and performance in a population of elite speed skaters.

An inspiratory muscle warm-up (IMW) was found to improve performance and lower lactate concentration in badminton players during specific footwork (Lin et al., 2007) and to significantly attenuate NIRS-derived deoxygenation (tissue saturation index, TSI) of the gastrocnemius muscle during submaximal and high-intensity intermittent sprint cycling exercises in elite female soccer players (Cheng et al., 2013). Moreover, the combination of a specific rowing warm-up with IMW led to a significant improvement in a 6-min all-out rowing effort compared to a specific rowing warm-up alone (Volianitis et al., 2001). However, IMW has not been investigated in a sprint speed skating race, notwithstanding this technique was found to improve 100-m race in elite swimmers (Wilson et al., 2014), Wingate test in field hockey players (Özdal et al., 2016), and intermittent running performance in healthy males (Tong and Fu, 2006).

Therefore, considering the potential cumulative impact of such techniques, the fact that elite athletes combine different methods, and in the spirit of answering a specific research question that was raised in preparation for the Olympic trials and competitions, the primary purpose of this study was to examine whether the combination of chronic RIPC with IMW could improve performance and modify muscular oxygenation during a 600-m speed-skating time-trial in elite speed skaters.

## MATERIALS AND METHODS

### Participants

Seven male elite long-track speed skaters (four with senior world cups and/or world championship experience, two with international junior championship experience, and one national level speed skater) volunteered for this study (age 23.4 ± 3.3 years, body height 181.79 ± 7.19 cm, and body mass 80.91 ± 7.72 kg). The limited number of high-level athletes available for this project is the main reason for the small sample size in this study. The athletes had 16 ± 6 years of experience in speed skating (short and long track), and their average weekly training volume was ∼13–15 h per week at the time of the study. The investigation took place during the training season and, therefore the timed-performances in the present study do not reflect the best potential results of the athletes. Personal best (Pb) for 500- and 1000-m races are presented as an indication of the level of the skaters (Pb500m: 35.26 ± 1.11 and Pb1000m: 69.19 ± 1.73). All participants provided written informed consent after being informed of the experimental procedures, associated risks, and potential benefits. The team physician approved the participation of the athletes for this research project. The study was approved by the local Institutional Ethics Committee (*Comité d'éthique de la Recherche en Sciences de la Santé*) and by the local Hospital Ethics Committee (*Comité d'éthique de la Recherche de l'IUCPQ-Université Laval*), and in accordance with the principles established in the Declaration of Helsinki.

## Experimental Design

All athletes were tested on two occasions in a randomized, single-blind, placebo-controlled, and crossover design. Specifically, the participants were blinded about the impact of the interventions, but the tester was aware of which protocol the subjects were undergoing and had undergone before. The athletes were blinded about their physiological, technical (push-off angle) and transponders (maximal velocity) data until the end of the research. However, to promote a realistic context, the athletes were not blinded about their performance (timing system) data. Athletes did not consume any caffeine, drugs, or supplements for 24 h before the tests and had a similar competition-specific diet before the two trials. All athletes participated in a maximal inspiratory pressure (MIP) testing session, were fully familiarized with IMW, RIPC, and SHAM procedures at least 14 days before the first race and the order of the two trials was interspersed with 7 days.

Maximal inspiratory pressure was recorded using the integrated mouth pressure meter of the Vmax ENCORE system (CareFusion) at the local hospital. The testing session was performed by an experienced professional operator and in conformity to standardized procedures (Gibson et al., 2002). Hans Rudolph mouthpieces standard type (clear) reusable series 9060 were used for the testing. A minimum of five and a maximum of nine technically satisfactory measurements were conducted, and the highest of three measurements with 5% variability or within 5 $cmH_2O$ difference was defined as maximum (Volianitis et al., 2001). The initial length of the inspiratory muscles was controlled by initiating each effort from residual volume. Verbal encouragement was given to assist the subjects perform maximally.

To minimize any placebo effect, participants were told that the study purpose was to compare the impact of two different combinations of preconditioning strategies (high intensity: $RIPC_{high\ pressure}$ + $IMW_{strength}$ or low intensity: $RIPC_{low\ pressure}$ + $IMW_{endurance}$) that could either alter arterial inflow and IM strength (COMBO) or micro perfusion and IM endurance capacity (SHAM). They were told that both combinations could potentially alter performance positively as follows: "*the aim of the study was to determine the best suitable combination of intervention individually for each of them*."

## Chronic Remote Ischemic Preconditioning

Remote ischemic preconditioning treatment implicated three alternating 5-min cycles of upper-limb compression interspaced with 5-min of reperfusion. The occlusion pressure was set at 180 mmHg (Lisbôa et al., 2017) in COMBO (mean systolic pressure: 116.7 ± 7.9 mmHg). The SHAM treatment followed the exact same procedure with a given pressure of 10 mmHg. In both conditions, participants were lying on their back on a massage table and one nylon blood pressure cuff (Welch Allyn, Skaneateles Falls, NY, United States or Almedic, Saint-Laurent, Montreal, QC, Canada) was positioned proximally around each arm. The size of the cuff was chosen in accordance to arm circumference, in respect to manufacturer instructions. Upper limbs were chosen for the treatment as the remote stimulation was shown to have a systemic vasoactive effect (Enko et al., 2011) and to alter performance (Barbosa et al., 2015). Furthermore, the large lower-body muscular mass and thigh circumference of elite speed skaters would necessitate a very high pressure to induce complete arterial blood flow blockage (Sharma et al., 2014) and, therefore, could implicate higher levels of subjective pain and a potential nocebo effect (Salvador et al., 2015). Both interventions (RIPC and SHAM) were conducted ~48, ~24, and ~1.5 h before the trials (the last compression cycle occurred ~60-min before the race). This chronic and acute RIPC protocol allowed the skaters to benefit from both the second window of conditioning (Yellon and Downey, 2003; Berger et al., 2015) and the early phase of conditioning (Yellon and Downey, 2003; Berger et al., 2015). It also allowed sufficient time to warm up (including IMW) and prepare according to usual competitive habits.

## Inspiratory Muscle Warm-Up

The protocol consisted of two sets of 30 breaths using a POWERbreathe (IMT Technologies Ltd., Birmingham, United Kingdom) at 40 and 15% MIP in IMW and SHAM, respectively, with a 60 s rest between sets (Lomax et al., 2011). Previous studies have indicated that specific IMW protocol at a given intensity of 40% MIP improves performance (Tong and Fu, 2006; Lin et al., 2007; Wilson et al., 2014). During the IMW trial, the subjects were instructed to initiate every breath from the residual volume and to continue the respiratory effort up to the lung volume where the IM force output for the given load limited further excursion of the thorax. During the SHAM trial, the breaths were performed gently and the respiratory time for each breath was protracted (Ohya et al., 2015). Both interventions were conducted only on racing days, after the athlete's off-ice warm-up, ~20-min before the time trials.

## Warm-Up

To promote a realistic context, the athletes were asked to reproduce their regular individual competition warm-up routine. However, the athletes awareness was raised on the fact that priming exercises can potentially influence peripheral oxygenation (Jones et al., 2006; Bailey et al., 2009; McIntyre and Kilding, 2015) in a similar way as the studied interventions (Salvador et al., 2015). Precisely, athletes were told that omitting to perform intensity bouts in their warm-ups 20–40-min before their race (Burnley et al., 2006; Bailey et al., 2009; Ingham et al., 2013) could potentially negatively affect their performance (Bailey et al., 2009) and mislead conclusion about the current research. Post-testing, all athletes reported having integrated priming exercises (~30-min before the race) in their off-ice warm-up as well of having reproduced a very similar warm-up in both conditions (**Table 1**).

## Speed Skating Measurements

### Time-Trials and Performance Measurements

The trials involved two 600-m race simulations on an indoor long-track (400-m) speed-skating oval approved for international competition. This distance was chosen in order to be able to compare the results of the present study (opener: 200-m + lap1:

**TABLE 1 |** Individual warm-up routine characterization including priming exercises and recovery time before the race for all speed skaters.

| Athlete | Low intensity exercises | Mobility drills and progressive dynamic exercises | Off-ice priming exercises | Time between priming exercises and race | On-ice warm-up (position, sprints, or pace) |
|---|---|---|---|---|---|
| 1 | | | 2 × 120 s (8/10) *r* = 1 | | |
| 2 | | | 90 s (7.5/10) | | |
| 3 | | | 195 s (6/10 to 8/10) | | |
| 4 | ∼5–10 min | ∼5–10 min | 8 × 10 s (4/10 to 8/10) | ∼30 min | Yes |
| 5 | | | 50 s (7/10) | | |
| 6 | | | 75 s (8/10) | | |
| 7 | | | 180 s (6/10 to 8/10) | | |

400-m = 600-m) with that of our previous speed-skating-RIPC investigation (opener: 200-m + lap1: 400-m + lap2: 400-m = 1000-m) (Richard and Billaut, 2018). The 1000-m time-trial was avoided to prevent the athletes from experiencing high-level of fatigue and to limit interference with training. Trials took place during a national center training camp in which the training prescription was similar for the 48 h before each trial. Environmental conditions were noted in both testing days (barometric pressure: 88.79 vs. 88.30 kPa, ice temperature: −5.5° vs. −5.2°, average ambient temperature: 15.8° vs. 14°). In both conditions, the athletes wore the same skin suit, started in the inner lane, and were asked to complete the 600-m in the fastest time possible. Verbal feedback was given by the coach to ensure competition-like conditions (Born et al., 2014). Depending on the stage of preparation of the athletes, it was at some occasions, possible for the other participants to see their teammates performed the test. However, the order of the tests and the chronology of the preparation of the athletes were the exact same in both conditions. During the races, all lap and split times we recorded using a timing system approved for international competition. Athletes were also wearing transponders approved for international competition (MYLAPS, Nijmegen, Netherlands) around each ankle to permit velocity measurements in different sections of the race.

### Technical Measurements

The effectiveness of the push-off (direction of the push-off force) is reflected by the angle *e* [push-off angle (*e*): the angle between the push-off leg and the horizontal] (Noordhof et al., 2014). Skating efficiency is reflected by smaller push-off angle and previous studies reported this angle as one of the key performance-determining variables (Noordhof et al., 2013). Therefore, participants were filmed from a frontal view in the first straight (inner lane) during both testing conditions with one digital high-definition camera (Canon, VIXIA HF R50, Tokyo, Japan). The camera was placed at the end of the inner lane straight, in the middle of the lane and tripod height was constant, in both conditions. The push-off angle was measured for the third, fourth, eighth, and ninth strides of the first straight using video-based movement analysis software (Dartfish). The frame approximately before the moment the hinge of the klapskate of the push-off leg opened was used to determine *e* for each stride. The average of theses four angles was deemed as the *e* for this section of the race. A correction for a slightly skewed camera position was made to the calculated *e* using the vertical coordinates of a horizontal marker that was present behind the skaters in the analyzed section (Noordhof et al., 2013).

## Physiological Measurements

### NIRS Measurements

Oxygenation patterns in the right vastus lateralis muscle were determined with a wireless portable NIRS device (PortaMon MkII, Artinis Medical Systems, Zetten, Netherlands). Bilateral oxygenation measurements would have provided a more complete dataset about the effects of the techniques investigated here considering the asymmetric oxygenation patterns reported in speed skating (Born et al., 2014; Hettinga et al., 2016). However, only one PortaMon device was available for this project. The right leg was particularly investigated as long-track speed skaters display a greater deoxygenation in the right leg compared to the left leg (Born et al., 2014; Hettinga et al., 2016). Investigating the right leg oxygenation profile also allows data comparison with previous studies on priming exercises (Bailey et al., 2009), IPC/RIPC (Paradis-Deschênes et al., 2017), IMW (Ohya et al., 2015), and slide board skating (Piucco et al., 2017).

The NIRS device was installed on the distal part of the vastus lateralis belly (15 cm above the proximal border of the patella). Skin fold thickness was measured at the site of application of the NIRS device (7.7 ± 2.5 mm) using a Harpenden Skinfold Caliper (Harpenden Ltd.) during the familiarization session, and was less than half the distance between the emitter and the detector (i.e., 20 mm). This thickness is adequate to let near-infrared light through muscle tissue (McCully and Hamaoka, 2000). The device was fixed using tape and covered with black bandages and the speed-skating skin suit to eliminate background light. Due to the influence of the site of investigation and adipose tissue thickness on the recorded NIRS parameters (Van Der Zwaard et al., 2016), the device position was marked with an indelible pen for the subsequent trial.

A modified form of the Beer–Lambert law, using two continuous wavelengths (760 and 850 nm) and a differential optical path length factor of 4.95 was used to calculate micromolar changes in tissue oxyhemoglobin–oxymyoglobin ([$O_2$HbMb]), deoxyhemoglobin–deoxymyoglobin [HHbMb], and total hemoglobin–myoglobin ([THbMb]) ([THbMb] = [$O_2$HbMb] + [HHbMb]), which is used as an index of change in regional blood volume (Van Beekvelt et al., 2001). The equilibrium between oxygen supply and consumption was calculated using the TSI (%) as [$HbO_2Mb$] divided by ([$O_2HbMb$] + [HHbMb]) × 100. The [HHbMb] signal was also taken as an indicator of tissue deoxygenation because this variable is less sensitive than [$O_2HbMb$] to perfusion variations and abrupt blood volume changes during contraction and recovery (Van Beekvelt et al., 2002; Ferrari et al., 2004; Grassi et al., 2007).

Data were acquired continuously at 10 Hz. A 10th order zero-lag low-pass Butterworth filter was applied to smooth NIRS signal (Faiss et al., 2013). Data were analyzed over the first 15 s (START) and between 15 and 40 s (END) as similarly described in a previous speed-skating investigation (Born et al., 2014) to allow for the comparison of oxygenation variables over effort of equal duration, and normalized to express the magnitude of changes from baseline.

### Heart Rate Measurements

Heart rate (HR) was monitored during racing using the athlete's personal monitoring devices: Polar M 400 (Polar Electro, Kempele, Finland) and Garmin Forerunner 920XT (Garmin, KS, United States). Average HR could not be extracted because of technical problems; however, max HR was collected for six of the seven athletes.

## Perceptual Measurements

Immediately after the races, rate of perceived exertion and rate of perceived breathlessness were measured using CR-10 Borg's scale (Ferreira et al., 2016). Expected benefit was also measured by asking athletes to rate their general expectation for both conditions considering their individual preparation, warm-up, readiness and the studied interventions on a scale from 1 to 10.

## Statistical Analyses

COMBO–SHAM differences were analyzed using Cohen's effect size (ES) ± 90% confidence limits, and magnitude-based inferences (Hopkins et al., 2009). We used this qualitative approach because traditional statistical approaches often do not indicate the magnitude of an effect, which is typically more relevant to athletic performance than any statistically significant effect (Hopkins et al., 2009). All variables were log-transformed before analysis (Hopkins et al., 2009), but raw data are reported as means or peaks ± SD for clarity. Magnitudes of difference between conditions were determined with an ES of 0.2 set to evaluate the smallest worthwhile change. Standardized effects were classified as small (>0.2), moderate (>0.5), or large (>0.8). Quantitative chances of greater or smaller values were assessed qualitatively as follows: 50 to 75%, possibly; 75 to 95%, likely; 95 to 99%, very likely; >99%, almost certainly. The effect was deemed "unclear" if chances of having better/greater and poorer/lower change in performance and physiological variables were both >5% (Hopkins et al., 2009).

# RESULTS

All participants met all the criteria for inclusion, and tolerated the RIPC and IMW procedure without complications. All participants completed the entire testing protocol (i.e., 2 × 600-m).

## Speed Skating Performance and Technical Variables

Individual and group mean performances are displayed in **Figure 1** and **Table 2**. COMBO had no clear effect on either overall performance (0.06% mean difference, ES 0.02; 90% confidence limits −0.09, 0.12) or pacing strategy. There was no clear effect of the intervention on maximal velocity measured with transponders in the first 200-m (54.20 ± 1.94 vs. 54.23 ± 2.16 km/h: 0.04% mean difference, ES 0.02; −0.24, 0.26) and in the last 400-m of the race (55.18 ± 1.51 vs. 55.30 ± 1.40 km/h: 0.21% mean difference, ES 0.07; −0.06, 0.19). Push-off angle (*e*) in the first straight also remained unaffected by the intervention (43.74 ± 1.75 vs. 43.80 ± 2.05°: 0.11% mean difference, ES 0.02; −0.17, 0.22).

## Physiological Variables

Maximal HR remained unaffected by the intervention (189.83 ± 7.36 vs. 189.83 ± 9.09 beats/min: −0.03% mean difference, ES −0.01; −0.26, 0.25).

There was no clear effect of the intervention on TSI, Δ[$O_2HbMb$] and Δ[THbMb] for both analyzed sections of the race. Mean and peak Δ[HHbMb] were also unaffected by the COMBO in the START section of the trial, however, mean Δ[HHbMb] was *likely* higher in the END section of the race (2.7%, ES 0.48; −0.07, 1.03) and peak Δ[HHbMb] was *possibly* higher in that same section (1.8%, ES 0.23; −0.10, 0.57) in COMBO compared with SHAM (**Table 2** and **Figure 2**).

## Perceptual Measures

Post-facto interviews completed at the end of the project revealed that none of the athletes knew there was a PLACEBO intervention indicating they were all confounded by the true objective of

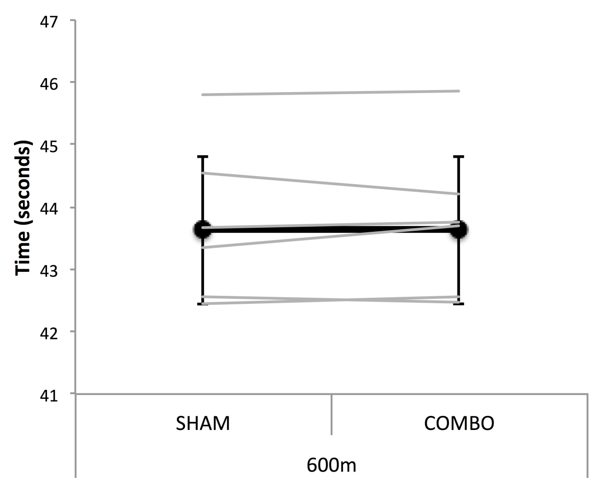


**FIGURE 1 |** Mean (black line) and individual (gray lines) performance time for the 600-m race simulation in SHAM and COMBO conditions. Data are presented as mean ± SD.

**TABLE 2 |** Physiological and performance measures for the on-ice 600-m time-trial.

| Variable | Time point | Intervention | | | | | | Likelihood of chances |
|---|---|---|---|---|---|---|---|---|
| | | SHAM | SD | COMBO | SD | *d* | CL | +ve/trivial/−ve |
| Tissue saturation index (TSI%) | 0–15 s | 44.32 | 2.62 | 44.45 | 3.05 | 0.04 | −0.47; 0.55 | 28/52/20 |
| | 15–40 s | 39.35 | 3.26 | 38.58 | 4.4 | −0.33 | −1.05; 0.38 | 10/27/63 |
| Tissue saturation index (TSI%)/baseline (% baseline) | 0–15 s | 75.1 | 3.8 | 75.4 | 5.8 | 0.04 | −0.55; 0.64 | 31/46/23 |
| | 15–40 s | 66.6 | 4.5 | 65.4 | 5.8 | −0.39 | −1.23; 0.45 | 11/23/66 |
| Average deoxyhemoglobin (HHbMb) | 0–15 s | 48.45 | 8.1 | 48.86 | 8.56 | 0.03 | −0.04; 0.11 | 0/100/0 |
| | 15–40 s | 54.86 | 9.5 | 56.37 | 9.83 | 0.12 | −0.02; 0.27 | 17/82/0 |
| Average deoxyhemoglobin (HHbMb)/baseline (% baseline) | 0–15 s | 113.8 | 5.4 | 114.6 | 5.5 | 0.13 | −0.17; 0.43 | 33/63/4 |
| | 15–40 s | 128.9 | 9.5 | 132.3 | 8.4 | 0.48 | −0.07; 1.03 | 82/15/3 |
| Peak deoxyhemoglobin (HHbMb) | 0–15 s | 58.86 | 10.39 | 59.16 | 10.52 | 0.02 | −0.15; 0.19 | 5/93/2 |
| | 15–40 s | 60.9 | 10.92 | 62.11 | 11.87 | 0.08 | −0.03; 0.19 | 4/96/0 |
| Peak deoxyhemoglobin (HHbMb)/baseline (% baseline) | 0–15 s | 138.2 | 9 | 138.8 | 7.5 | 0.07 | −0.45; 0.58 | 32/51/18 |
| | 15–40 s | 142.8 | 8.6 | 145.4 | 9.9 | 0.23 | −0.10; 0.57 | 58/40/2 |
| Oxyhemoglobin (O2HbMb) | 0–15 s | 36.17 | 4.16 | 36.9 | 4.07 | 0.16 | −0.18; 0.49 | 40/55/4 |
| | 15–40 s | 34.18 | 4.34 | 35.25 | 5.15 | 0.22 | −0.27; 0.71 | 53/40/7 |
| Oxyhemoglobin (O2HbMb)/baseline (% baseline) | 0–15 s | 66.8 | 5.4 | 68.1 | 4.4 | 0.21 | −0.24; 0.66 | 52/42/6 |
| | 15–40 s | 63.1 | 4.7 | 64.9 | 5.4 | 0.29 | −0.36; 0.95 | 60/30/10 |
| Total hemoglobin (THb) | 0–15 s | 84.62 | 11.55 | 85.76 | 12.14 | 0.08 | −0.08; 0.24 | 10/90/1 |
| | 15–40 s | 89.04 | 12.77 | 90.11 | 13.12 | 0.07 | −0.07; 0.22 | 7/93/1 |
| Total hemoglobin (THb)/baseline (% baseline) | 0–15 s | 87.4 | 3.3 | 88.5 | 2.4 | 0.29 | −0.30; 0.88 | 61/31/8 |
| | 15–40 s | 91.9 | 3.6 | 92.9 | 2.6 | 0.26 | −0.27; 0.79 | 59/34/7 |
| Maximal heart rate, beats/min | During 600 m | 189.3 | 7.36 | 189.3 | 9.09 | −0.01 | −0.26; 0.25 | 8/82/10 |
| Push-off angle (e),° | First straight | 43.74 | 1.75 | 43.8 | 2.05 | 0.02 | −0.17; 0.22 | 6/90/3 |
| Maximal velocity, km/h | First 200-m | 54.2 | 1.94 | 54.23 | 2.16 | 0.01 | −0.24; 0.26 | 9/83/8 |
| | Last 400-m | 55.18 | 1.51 | 55.3 | 1.4 | 0.07 | −0.06; 0.19 | 4/96/0 |
| Time (performance), seconds | 200-m | 17.19 | 0.55 | 17.23 | 0.6 | 0.08 | −0.08; 0.24 | 10/89/1 |
| | 600-m | 43.63 | 1.19 | 43.63 | 1.19 | 0.02 | −0.09; 0.12 | 1/99/0 |

the study. Interestingly however, expected perceived benefits were *possibly* higher (4.1%, ES 0.35; −0.22, 0.91) in COMBO (7.71/10 ± 0.57) compared to SHAM (7.43/10 ± 0.79), but no difference were observed in rate of perceived exertion (SHAM: 8.36/10 ± 0.63, COMBO: 8.43/10 ± 0.61) and rate of perceived breathlessness (SHAM: 8/10 ± 0.65, COMBO: 7.86/10 ± 1.18) between conditions.

## DISCUSSION

The primarily purpose of this investigation was to test the potential ergogenic impact of a combination of preconditioning strategies, that were previously found to enhance performance in predominantly anaerobic oriented exercises (Wilson et al., 2014; Salvador et al., 2015; Özdal et al., 2016), on a 600-m time-trial in elite speed skaters. This study also examined the impact of the combination of RIPC and IMW, two preconditioning strategies that were found to modify peripheral oxygenation (Cheng et al., 2013; Kido et al., 2015; Tanaka et al., 2016) in some context, on the vascular and metabolic effects induced by the crouched position adopted by elite speed skaters in race. Considering the certain level of permeability that we previously observed in elite speed skaters regarding acute RIPC (Richard and Billaut, 2018), and since elite athletes present a narrower window of adaptation compared to less trained individuals (Marocolo et al., 2016a) and tend to combine different methods to enhance their performances (Kilduff et al., 2013; McGowan et al., 2015), we reasoned that the aggregation of such techniques could be necessary to trigger an ergogenic response and to enhance performance in this population. However, the current data showed no performance-enhancing effect (split time, final time, and velocities) of COMBO on an all-out 600-m speed-skating time trial lasting ∼43 s, and indicated that the addition of this intervention to an elite long-track skater's competitive warm-up routine is insignificant in regard to performance. Furthermore, skating efficiency, which is reflected by push-off angle (*e*) (Noordhof et al., 2013) was not affected by combo in the analyzed section of the race (first straight). Besides, although most of the physiological data were negligibly influenced by COMBO, mean and peak Δ[HHbMb] were respectively *likely* and *possibly* increase in the END portion of the race, which may presumably be related to a higher $O_2$ extraction at the muscular level.

### Preconditioning Strategies in Elite Sprint Speed Skaters

This investigation that took place during the training season revealed that a combination of preconditioning strategies does

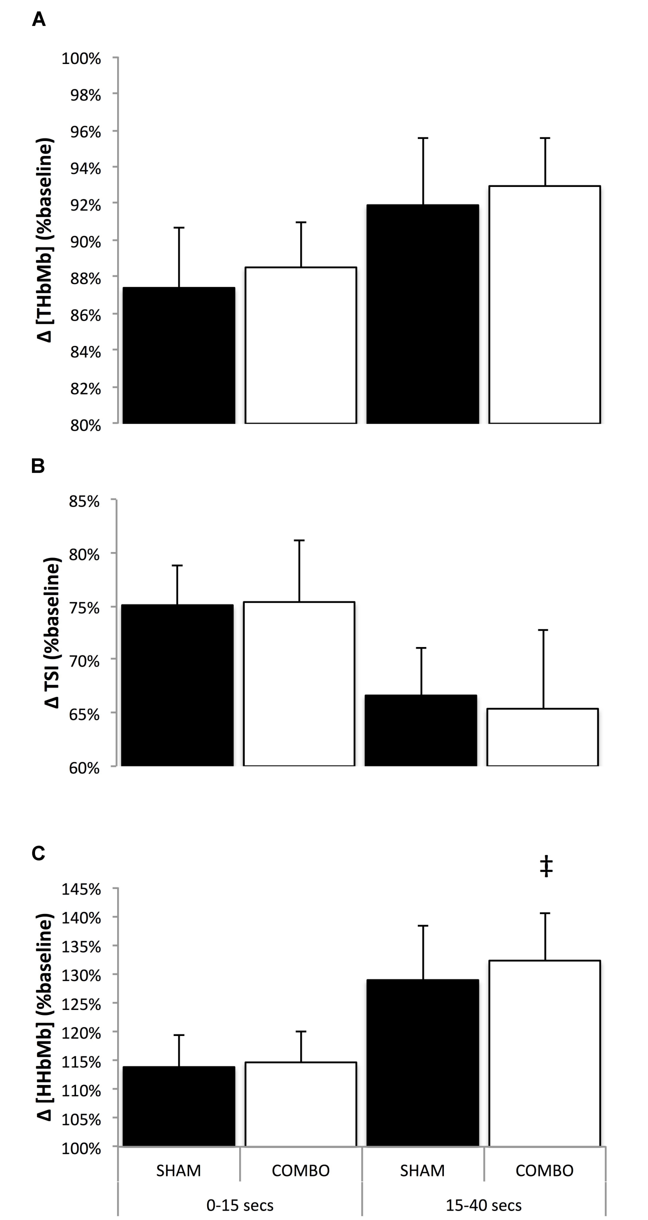


**FIGURE 2 |** Mean changes in [THbMb] **(A)**, TSI **(B)**, and [HHbMb] **(C)** for the first 15 s (0–15 s), and from second 15 to second 40 (15–40 s) in SHAM and COMBO conditions. Black bars (SHAM) and white bars (COMBO). Data are presented as mean ± SD. ‡Likely clear effect in COMBO vs. SHAM.

not improve speed skating 600-m time-trial performance. The current findings contrasts with the results of a meta-analysis on the effect of IPC on performance that reported a small but clear effect of this intervention (ES 0.23) on exercises lasting 10–90 s (Salvador et al., 2015). The present findings also contrast with studies reporting an ergogenic effect of IMW on a 100-m swimming performance (∼75 s) and on a Wingate test (Özdal et al., 2016). Therefore, we propose that the peculiar characteristics of speed skating (Konings et al., 2015; Hettinga et al., 2016), the high level of the athletes included in our study or a mix of these two factors, may contribute to explaining our findings.

On the one hand, Salvador et al. (2015) found no evidence for a greater benefit of IPC in less fit individuals compared to athletes in their meta-analysis. However, the current available literature contains very few studies investigating the effect of IPC/RIPC in high-level elite athlete populations (Incognito et al., 2015). In that regard, it has been suggested that highly trained subjects are expected to have high NOS activity (McConell et al., 2007). This higher skeletal muscle NOS protein expression (nNOSμ) is likely to be associated with greater production of NO by skeletal muscle, which might render this population less dependent on the NO pathway (McConell et al., 2007). NO seems to be a key factor in the mechanistic response to RIPC (Incognito et al., 2015), thereby potentially minimizing the effect of such an intervention in an elite athlete population (Richard et al., 2018). On the other hand, the two above-mentioned IMW studies included respectively high-level swimmers and field hockey players, which contribute to making the comparison easier with our study. Nevertheless, the fact that swimming, a sport that presents several unique challenges to the respiratory system (Wilson et al., 2014), was investigated in the former of theses two investigations, and the fact that the latter IMW study was not placebo-controlled (Özdal et al., 2016) may naturally contribute to explaining theses positive outcomes. Besides, the potential ergogenic effect of COMBO might also have been impeded completely or in part by the sport-specific reduced blood flow associated with the low skating position, the relatively long gliding phase and the high intramuscular forces specific to speed skating (Konings et al., 2015). Therefore, based on the available data, it can be misleading to speculate whether the level of the athletes, the characteristics of the sport, or the combined efficiency of the tested techniques may be deemed as the main reason of absence of ergogenic impact observed in our study.

## Expected Benefits and Performance

Although the athletes were (*possibly*) expecting greater benefits in COMBO than in SHAM condition (considering their global preparation, including the interventions), these higher expectations (ES: 0.35) did not translate into an improved performance. In fact, it is worth highlighting that, after performing their individual competitive warm-up, both COMBO and SHAM yielded an identical time of 43.63 ± 1.19 s. The results of other investigations suggest that, the effect of IPC does not surpass a placebo intervention and/or that the ergogenic effect associated with IPC may be mainly attributed to a placebo effect (Marocolo et al., 2015; Succi, 2016). After the study, when we debriefed the athletes in regard to the true SHAM interventions, none of them were aware of the presence of any placebo procedures. Therefore, their higher expectation may have been mainly related to their general preparation rather than to the COMBO *per se*. Another interesting finding is that both IPC and SHAM interventions led to performance improvements on a resistance exercise test (∼40 s, such as in the present study), but these ergogenic effects faded over time (over only four trials) (Marocolo et al., 2016b). While these results suggests that performance improvement after IPC (or SHAM) may mainly be attributable to motivational issues, the fact that these ergogenic effects tend to fade away with time decreases the practical value of such interventions in an elite sport setting where athletes compete on a regular basis.

## Accentuated Deoxygenation

Although performance was unaffected by COMBO, muscle deoxygenation was accentuated (higher mean and peak [HHbMb]) in the END section of the race. Interestingly, a similar enhanced [HHbMb] response was observed after acute RIPC, only in sprint specialized skaters, during a 1000-m speed skating time trial (Richard and Billaut, 2018). This response was observed during the entire 1000-m race (∼75 s) and was concomitant with a possible increase in blood volume ([THbMb]) in the middle section of the race only. Taken these data together, it can be hypothesized that the analogous ([HHbMb]) response observed in the present investigation occurred because most of the athletes included in the study were sprint-specialized skaters. Indeed, when further studying the specific response of the four sprint-specialized skaters of international senior level (Pb 500-m, 34.45 ± 0.3, Pb 1000-m: 67.97 ± 0.36) in a post-facto analysis, we observed a likely enhanced ([HHbMb]) in the END section of the race (mean [HHbMb]: 3.6%, ES 0.56; −0.20, 1.33 and peak [HHbMb]: 2.7%, ES 0.42; −0.18, 1.01) that was greater than the whole group response. However, in the present study, this greater $O_2$ extraction was not accompanied by a clear effect on [THbMb], a surrogate of blood volume, either for the whole group or the four international level sprinters. In the aforementioned RIPC-speed-skating study, it was not ruled out that an increase in [THbMb] might have been accountable for the enhanced [HHbMb] for the middle section of the race in sprint athletes. In fact, sprinters typically present a high proportion of type II fibers (which are displaying a lower microvascular $O_2$ partial pressure; McDonough et al., 2005; Cleland et al., 2012; Paradis-Deschênes et al., 2016) and, thus, an increase in blood volume is more likely to lead to higher $O_2$ extraction in these conditions. However, since this concomitant response was not observed in the other sections of the race in the RIPC-speed skating study and considering the results of the present investigation, available data rather suggests that COMBO increased [HHbMb] *per se.*

Importantly, while RIPC was found to accentuate deoxygenation (Barbosa et al., 2015; Paradis-Deschênes et al., 2016) and accelerate deoxygenation dynamics (Kido et al., 2015; Tanaka et al., 2016) in some studies, Cheng et al. (2013) reported that the addition of IMW to a whole-body warm-up significantly attenuates deoxygenation during a high-intensity intermittent sprint test. Therefore, in that perspective, interference in the physiological response of the two used preconditioning strategies cannot be excluded.

## Warm-Up Protocol, Local Hemodynamic, and Performance Enhancement

A priming exercise was found to enhance tolerance to high-intensity exercise with a concomitant significant increase in the [HHbMb] primary amplitude (Bailey et al., 2009), a physiological response that is similar to that observed after RIPC/IPC in some contexts (Kido et al., 2015; Tanaka et al., 2016). However, studies demonstrating IPC/RIPC as ergogenic reported that performance changes were associated with varied deoxygenation patterns [attenuated (Kido et al., 2015; Patterson et al., 2015), accentuated (Barbosa et al., 2015; Paradis-Deschênes et al., 2016), and accelerated dynamics (Kido et al., 2015; Tanaka et al., 2016)]. Moreover, an attenuated muscular deoxygenation was observed after IMW during submaximal and high-intensity intermittent sprint cycling, but this response was not accompanied by an improved performance (Cheng et al., 2013). In long-track speed skating, an enhanced deoxygenation was observed during the gliding and push-off phases of the skating cycle (Hettinga et al., 2016). Although this accentuated deoxygenation may intuitively seem to be deleterious to skating performance, its acute impact on performance remains equivocal from a physiological perspective. Hence, studies investigating the impact of changes in muscle deoxygenation on muscle functioning and performance are still required.

Kjeld et al. (2014) reported performance improvements in three tests after IPC, however, importantly, the least-improved test (1 vs. 8 and 17%) was the only one preceded with a warm-up and priming exercises. In the current investigation, all athletes reported having integrated intense priming exercises to their warm-up routine (**Table 1**). Therefore, since physical activity may elicit a similar preconditioning response to RIPC/IPC (Lalonde et al., 2015; Salvador et al., 2015), it is plausible that the effect of RIPC on performance and local metabolism are limited in field studies that investigate elite athletes who typically perform complete warm-up routines (McGowan et al., 2015; Richard and Billaut, 2018).

## Limitations and Perspectives

These results suggest that COMBO has no practical ergogenic effect on exercise performance in elite speed skaters; therefore the practical applications of combining ischemic preconditioning with IMW appear limited considering the logistical efforts associated with using these techniques in the field. That said, COMBO should be investigated in the context of short-track speed skating since this sport induces a greater ischemic stress compared to long-track speed skating and might therefore benefit from this combination to a greater extent (Hettinga et al., 2016).

Remote ischemic preconditioning treatments were practiced 48, 24, and 1 h before trials, which falls within both the first and the late conditioning phases (Berger et al., 2015). Since ergogenic effects of RIPC/IPC have been observed within a very short time frame (5- to 10-min) (de Groot et al., 2010; Paradis-Deschênes et al., 2016), and up to 8 h (Lisbôa et al., 2017) with respect to the first phase of conditioning, and considering the scarcely studied impact of the second window of condition in sport settings (Seeger et al., 2017), we cannot rule out the influence of the timing on the current speed-skating performances.

To promote a realistic context, the athletes were not blinded about their performance data (timing system). However, the unchanged rates of perceived exertion suggest that the effort was similar between conditions. The limited pacing possibilities in such a sprint distance also minimize the potential impact of this limitation. The current investigation was conducted during a training camp. While very similar training conditions preceded both testing days, this context may implicate varied fatigue levels among athletes (17 training sessions in 14 days with six intense training sessions including the trials). Nevertheless, some of those limitations contribute to mimicking a more genuine and realistic competitive environment and seldom differences in sensations between the two races were reported by the athletes in post-facto interviews (one minor technical issue). Similarly, although studying the effect of a combination of preconditioning strategies contributes to ensuring a very field-specific study context and increases the likelihood of applicability of the results, this experimental model does not permit to assess the individual impact of each technique (chronic RIPC vs. acute RIPC vs. IMW).

The small sample size is a limitation in this study. However, investigation of elite athletes is underrepresented in the literature, and the strength of the sample and originality of the findings reside in its specificity.

## CONCLUSION

The results of this investigation suggest that the combination of chronic RIPC with IMW may have a limited effect as a strategy to improve exercise performance and gain a competitive advantage in elite long-track speed skaters. While COMBO led to small and moderate increases in leg muscle deoxygenation, this did not affect performance. Thus, the relationship between changes in muscle oxygenation and performance remains equivocal, at least in speed skating, and further studies will need to better understand the impact of such peripheral changes. In the perspectives of training beyond PyeongChang 2018, it is certain that athletes will continue combining ergogenic aids and techniques in the hope of enhancing their physiological responses, and it is critical that research in the sport sciences keeps up with such practices and assess the efficacy of these interactions.

## DATA AVAILABILITY STATEMENT

All relevant data is contained within the manuscript but ungroup individual performance data are not publicly available for ethical reasons; publishing them may render possible to recognize the athletes.

## AUTHOR CONTRIBUTIONS

PR and FB conceived and designed the research, interpreted the results, and edited and revised the manuscript for approval of the final version. PR collected and analyzed the data, and drafted the manuscript.

## FUNDING

The work described here was not funded by any grant. Funding sources originated from sport organizations that finance the team activities (CNGB/SSC, FPVQ, and ESQL). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

## ACKNOWLEDGMENTS

The authors would like to thank the CNGB/SSC, FPVQ, and ESQL for their support. Special thanks to the athletes, coaches, and stakeholders.

## REFERENCES

Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., Dimenna, F. J., and Jones, A. M. (2009). Optimizing the 'priming' effect: in uence of prior exercise intensity and recovery duration on o 2 uptake kinetics and severe-intensity exercise tolerance. *J. Appl. Physiol.* 107, 1743–1756. doi: 10.1152/japplphysiol.00810.2009

Barbosa, T. C., Machado, A. C., Braz, I. D., Fernandes, I. A., Vianna, L. C., Nobrega, A. C. L., et al. (2015). Remote ischemic preconditioning delays fatigue development during handgrip exercise. *Scand. J. Med. Sci. Sports* 25, 356–364. doi: 10.1111/sms.12229

Berger, M., Macholz, F., Mairbäurl, H., and Bartsch, P. (2015). Remote ischemic preconditioning for prevention of high altitude diseases: fact or fiction? *J. Appl. Physiol.* 119, 1143–1151. doi: 10.1152/japplphysiol.00156.2015

Born, D. P., Zinner, C., Herlitz, B., Richter, K., Holmberg, H. C., and Sperlich, B. (2014). Muscle oxygenation asymmetry in ice speed skaters: not compensated by compression. *Int. J. Sports Physiol. Perform.* 9, 58–67. doi: 10.1123/IJSPP.2012-0210

Burnley, M., Doust, J. H., and Jones, A. M. (2006). Time required for the restoration of normal heavy exercise v following prior heavy exercise. *J. Appl. Physiol.* 101, 1320–1327. doi: 10.1152/japplphysiol.00475.2006

Cheng, C. F., Tong, T. K., Kuo, Y. C., Chen, P. H., Huang, H. W., and Lee, C. L. (2013). Inspiratory muscle warm-up attenuates muscle deoxygenation during cycling exercise in women athletes. *Respir. Physiol. Neurobiol.* 186, 296–302. doi: 10.1016/j.resp.2013.02.029

Cleland, S. M., Murias, J. M., Kowalchuk, J. M., and Paterson, D. H. (2012). Effects of prior heavy-intensity exercise on oxygen uptake and muscle deoxygenation kinetics of a Subsequent heavy-intensity cycling and knee-extension exercise. *Appl. Physiol. Nutr. Metab.* 37, 138–148. doi: 10.1139/h11-143

Enko, K., Nakamura, K., Yunoki, K., Miyoshi, T., Akagi, S., Yoshida, M., et al. (2011). Intermittent arm ischemia induces vasodilatation of the contralateral upper limb. *J. Physiol. Sci.* 61, 507–513. doi: 10.1007/s12576-011-0172-9

Faiss, R., Léger, B., Vesin, J. M., Fournier, P. E., Eggel, Y., Dériaz, O., et al. (2013). Significant molecular and systemic adaptations after repeated sprint training in hypoxia. *PLoS One* 8:e56522. doi: 10.1371/journal.pone.0056522

Ferrari, M., Mottola, L., and Quaresima, V. (2004). Principles, techniques, and limitations of near infrared spectroscopy. *Can. J. Appl. Physiol.* 29, 463–487. doi: 10.1002/0471238961.0914061810151405.a01.pub2

Ferreira, T. N., Sabino-Carvalho, J. L., Lopes, T. R., Ribeiro, I. C., Succi, J. E., da Silva, A. C., et al. (2016). Ischemic preconditioning and repeated sprint swimming: a placebo and nocebo study. *Med. Sci. Sports Exerc.* 48, 1967–1975. doi: 10.1249/MSS.0000000000000977

Foster, G. P., Giri, P. C., Rogers, D. M., Larson, S. R., and Anholm, J. D. (2014). Ischemic preconditioning improves oxygen saturation and attenuates hypoxic pulmonary vasoconstriction at high altitude. *High Alt. Med. Biol.* 15, 155–161. doi: 10.1089/ham.2013.1137

Gibson, G. J., Whitelaw, W., Siafakas, N., Supinski, G. S., Fitting, J. W., Bellemare, F., et al. (2002). ATS/ERS statement on respiratory muscle testing. *Am. J. Respir. Crit. Care Med.* 166, 518–624. doi: 10.1164/rccm.166.4.518

Grassi, B., Marzorati, M., Lanfranconi, F., Ferri, A., Longaretti, M., Stucchi, A., et al. (2007). Impaired oxygen extraction in metabolic myopathies: detection and quantification by near-infrared spectroscopy. *Muscle Nerve* 35, 510–520. doi: 10.1002/mus.20708

de Groot, P. C., Thijssen, D. H. J., Sanchez, M., Ellenkamp, R., and Hopman, M. T. E. (2010). Ischemic preconditioning improves maximal performance in humans. *Eur. J. Appl. Physiol.* 108, 141–146. doi: 10.1007/s00421-009-1195-2

Hettinga, F. J., Konings, M. J., and Cooper, C. E. (2016). Differences in muscle oxygenation, perceived fatigue and recovery between long-track and short-track speed skating. *Front. Physiol.* 7:619. doi: 10.3389/fphys.2016.00619

Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.* 41, 3–12. doi: 10.1249/MSS.0b013e31818cb278

Incognito, A. V., Burr, J. F., and Millar, P. J. (2015). The effects of ischemic preconditioning on human exercise performance. *Sports Med.* 46, 531–544. doi: 10.1007/s40279-015-0433-5

Ingham, S. A., Fudge, B. W., Pringle, J. S., and Jones, A. M. (2013). Improvement of 800-m running performance with prior high-intensity exercise. *Int. J. Sports Physiol. Perform.* 8, 77–83.

Jones, A. M., Berger, N. J. A., Wilkerson, D. P., and Roberts, C. L. (2006). Effects of 'priming' exercise on pulmonary o2 uptake and muscle deoxygenation kinetics during heavy-intensity cycle exercise in the supine and upright positions. *J. Appl. Physiol.* 101, 1432–1441. doi: 10.1152/japplphysiol.00436.2006

Kido, K., Suga, T., Tanaka, D., Honjo, T., Homma, T., Fujita, S., et al. (2015). Ischemic preconditioning accelerates muscle deoxygenation dynamics and enhances exercise endurance during the work-to-work test. *Physiol. Rep.* 3, e12395–e12395. doi: 10.14814/phy2.12395

Kilduff, L. P., Finn, C. V., Baker, J. S., Cook, C. J., and West, D. J. (2013). Preconditioning strategies to enhance physical performance on the day of competition. *Int. J. Sports Physiol. Perform.* 8, 677–681.

Kjeld, T., Rasmussen, M. R., Jattu, T., Nielsen, H. B., and Secher, N. H. (2014). Ischemic preconditioning of one forearm enhances static and dynamic apnea. *Med. Sci. Sports Exerc.* 46, 151–155. doi: 10.1249/MSS.0b013e3182a4090a

Konings, M. J., Elferink-Gemser, M. T., Stoter, I. K., van der Meer, D., Otten, E., and Hettinga, F. J. (2015). Performance characteristics of long-track speed skaters: a literature review. *Sports Med.* 45, 505–516. doi: 10.1007/s40279-014-0298-z

Lalonde, F., Poirier, P., Arvisais, D., and Curnier, D. (2015). Exercise-induced ischemic preconditioning and the potential application to cardiac rehabilitation. *J. Cardiopulm. Rehabil. Prev.* 35, 93–102. doi: 10.1097/HCR.0000000000000099

Lin, H., Tong, T. K., Huang, C., Nie, J., Lu, K., and Quach, B. (2007). Specific inspiratory muscle warm-up enhances badminton footwork performance. *Appl. Physiol. Nutr. Metab.* 32, 1082–1088. doi: 10.1139/H07-077

Lisbôa, F. D., Turnes, T., Cruz, R. S., Raimundo, J. A., Pereira, G. S., and Caputo, F. (2017). The time dependence of the effect of ischemic preconditioning on successive sprint swimming performance. *J. Sci. Med. Sport* 20, 507–511. doi: 10.1016/j.jsams.2016.09.008

Lomax, M., Grant, I., and Corbett, J. (2011). Inspiratory muscle warm-up and inspiratory muscle training: separate and combined effects on intermittent running to exhaustion. *J. Sports Sci.* 29, 563–569. doi: 10.1080/02640414.2010.543911

Marocolo, M., da Mota, G. R., Pelegrini, V., and Appell Coriolano, H. J. (2015). Are the beneficial effects of ischemic preconditioning on performance partly a placebo effect? *Int. J. Sports Med.* 36, 822–825. doi: 10.1055/s-0035-1549857

Marocolo, M., da Mota, G. R., Simim, M. A., and Appell Coriolano, H. J. (2016a). Myths and facts about the effects of ischemic preconditioning on performance. *Int. J. Sports Med.* 37, 87–96. doi: 10.1055/s-0035-1564253

Marocolo, M., Marocolo, I. C., da Mota, G. R., Simão, R., Maior, A. S., and Coriolano, H.-J. (2016b). Beneficial effects of ischemic preconditioning in resistance exercise fade over time. *Int. J. Sports Med.* 37, 819–824. doi: 10.1055/s-0042-109066

McConell, G. K., Bradley, S. J., Stephens, T. J., Canny, B. J., Kingwell, B. A., and Lee-Young, R. S. (2007). Skeletal muscle nnosu protein content is increased by exercise training in humans. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 293, R821–R828. doi: 10.1152/ajpregu.00796.2006

McCully, K. K., and Hamaoka, T. (2000). Near-infrared spectroscopy: what can it tell us about oxygen saturation in skeletal muscle? *Exerc. Sport Sci. Rev.* 28, 123–1237. doi: 10.1117/1.2805437

McDonough, P., Behnke, B. J., Padilla, D. J., Musch, T. I., and Poole, D. C. (2005). Control of microvascular oxygen pressures in rat muscles comprised of different fibre types. *J. Physiol.* 563(Pt 3), 903–913. doi: 10.1113/jphysiol.2004.079533

McGowan, C. J., Pyne, D. B., Thompson, K. G., and Rattray, B. (2015). Warm-Up strategies for sport and exercise: mechanisms and applications. *Sports Med.* 45, 1523–1546. doi: 10.1007/s40279-015-0376-x

McIntyre, J. P., and Kilding, A. E. (2015). Effects of high-intensity intermittent priming on physiology and cycling performance. *J. Sports Sci.* 33, 561–567. doi: 10.1080/02640414.2014.960882

Noordhof, D. A., Foster, C., Hoozemans, M. J., and de Koning, J. J. (2013). Changes in speed skating velocity in relation to push-off effectiveness. *Int. J. Sports Physiol. Perform.* 8, 188–194.

Noordhof, D. A., Foster, C., Hoozemans, M. J. M., and de Koning, J. J. (2014). The association between changes in speed skating technique and changes in skating velocity. *Int. J. Sports Physiol. Perform.* 9, 68–76. doi: 10.1123/IJSPP.2012-0131

Ohya, T., Hagiwara, M., and Suzuki, Y. (2015). Inspiratory muscle warm-up has no impact on performance or locomotor muscle oxygenation during high-intensity intermittent sprint cycling exercise. *SpringerPlus* 4:556. doi: 10.1186/s40064-015-1355-2

Özdal, M., Bostanci, Ö, Dağlioğlu, Ö, Ağaoğlu, A., and Kabadayi, M. (2016). Effect of respiratory warm-up on anaerobic power. *J. Phys. Ther. Sci.* 28, 2097–2298. doi: 10.1589/jpts.28.2097

Paradis-Deschênes, P., Joanisse, D. R., and Billaut, F. (2016). Ischemic preconditioning increases muscle perfusion, oxygen uptake and force in strength-trained athletes. *Appl. Physiol. Nutr. Metab.* 41, 938–944. doi: 10.1139/apnm-2015-0561

Paradis-Deschênes, P., Joanisse, D. R., and Billaut, F. (2017). Sex-specific impact of ischemic preconditioning on tissue oxygenation and maximal concentric force. *Front. Physiol.* 7:674. doi: 10.3389/fphys.2016.00674

Patterson, S. D., Bezodis, N. E., Glaister, M., and Pattison, J. R. (2015). The effect of ischemic preconditioning on repeated sprint cycling performance. *Med. Sci. Sports Exerc.* 47, 1652–1658. doi: 10.1249/MSS.0000000000000576

Piucco, T., Soares, R., Diefenthaeler, F., Millet, G. Y., and Murias, J. M. (2017). V̇O2 and muscle deoxygenation kinetics during skating: comparison between slide board and treadmill skating. *Int. J. Sports Physiol. Perform.* doi: 10.1123/ijspp.2015-0012 [Epub ahead of print].

Richard, P., and Billaut, F. (2018). Time-trial performance in elite speed skaters after remote ischemic preconditioning. *Int. J. Sports Physiol. Perform.* doi: 10.1123/ijspp.2018-0111 [Epub ahead of print].

Richard, P., Kosiris, L. P., Charbonneau, M., Naulleau, C., Tremblay, J., and Billaut, F. (2018)). Time-trial performance in world-class speed skaters after chronic nitrate ingestion. *Int. J. Sports Physiol. Perform.* doi: 10.1123/ijspp.2017-0724 [Epub ahead of print].

Rundell, K. W., Nioka, S., and Chance, B. (1997). Hemoglobin/myoglobin desaturation during speed skating. *Med. Sci. Sports Exerc.* 29, 248–258. doi: 10.1097/00005768-199702000-00014

Salvador, A. F., De Aguiar, R. A., Lisbôa, F. D., Pereira, K. L., Cruz, R. S., and Caputo, F. (2015). Ischemic preconditioning and exercise performance: a systematic review and meta-analysis. *Int. J. Sports Physiol. Perform.* 11, 4–14. doi: 10.1123/ijspp.2015-0012

Seeger, J. P., Timmers, S., Ploegmakers, D. J., Cable, N. T., Hopman, M. T., and Thijssen, D. H. (2017). Is delayed ischemic preconditioning as effective on running performance during a 5 km time trial as acute IPC? *J. Sci. Med. Sport.* 20, 208–212. doi: 10.1016/j.jsams.2016.03.010

Sharma, V., Cunniffe, B., Verma, A. P., Cardinale, M., and Yellon, D. (2014). Characterization of acute ischemia-related physiological responses associated with remote ischemic preconditioning: a randomized controlled, crossover human study. *Physiol. Rep.* 2:e12200. doi: 10.14814/phy2.12200

Succi, E. (2016). Effect of ischemic preconditioning on endurance performance does not surpass placebo. *Med. Sci. Sports Exerc.* 49, 124–132. doi: 10.1249/MSS.0000000000001088

Tanaka, D., Suga, T., Tanaka, T., Kido, K., Honjo, T., Fujita, S., et al. (2016). Ischemic preconditioning enhances muscle endurance during sustained isometric exercise. *Physiol. Biochem.* 37, 614–618. doi: 10.1055/s-0035-1565141

Tong, T. K., and Fu, F. H. (2006). Effect of specific inspiratory muscle warm-up on intense intermittent run to exhaustion. *Eur. J. Appl. Physiol.* 97, 673–680. doi: 10.1007/s00421-006-0233-6

Van Beekvelt, M. C., Colier, W. N., Wevers, R. A., and Van Engelen, B. G. (2001). Performance of near-infrared spectroscopy in measuring local o2 consumption and blood flow in skeletal muscle. *J. Appl. Physiol.* 90, 511–519.

Van Beekvelt, M. C., Van Engelen, B. G., Wevers, R. A., and Colier, W. (2002). *In vivo* quantitative near-infrared spectroscopy in skeletal muscle during incremental isometric handgrip exercise. *Clin. Physiol. Funct. Imaging* 22, 210–217. doi: 10.1046/j.1475-097X.2002.00420.x

Van Der Zwaard, S., Jaspers, R. T., Blokland, I. J., Achterberg, C., Visser, J. M., Den Uil, A. R., et al. (2016). Oxygenation threshold derived from near- infrared spectroscopy: reliability and its relationship with the first ventilatory threshold. *PLoS One* 11:e0162914. doi: 10.1371/journal.pone.0162914

Volianitis, S., McConnell, A. K., Koutedakis, Y., and Jones, D. A. (2001). Specific respiratory warm-up improves rowing performance and exertional dyspnea. *Med. Sci. Sports Exerc.* 33, 1189–1193. doi: 10.1097/00005768-200107000-00017

Wilson, E. E., McKeever, T. M., Lobb, C., Sherriff, T., Gupta, L., Hearson, G., et al. (2014). Respiratory muscle specific warm-up and elite swimming performance. *Br. J. Sports Med.* 48, 789–791. doi: 10.1136/bjsports-2013-092523

Yellon, D. M., and Downey, J. M. (2003). Preconditioning the myocardium: from cellular physiology to clinical cardiology. *Physiol. Rev.* 83, 1113–1151. doi: 10.1152/physrev.00009.2003

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Physiology

REVIEW
published: 20 June 2018
doi: 10.3389/fphys.2018.00770

# Physiological and Physical Profile of Snowboarding: A Preliminary Review

**Gianluca Vernillo[1,2]*, Cesare Pisoni[3] and Gabriele Thiébat[3,4]**

[1] Department of Biomedical Sciences for Health, University of Milan, Milan, Italy, [2] Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Calgary, AB, Canada, [3] Snowboard and Freestyle Sector, Italian Winter Sports Federation, Milan, Italy, [4] Sports Trauma Centre, IRCCS Institute Orthopedic Galeazzi, Milan, Italy

The sport of snowboarding has grown in popularity as both a recreational winter activity as well as a prominent Olympic sport. Both forms are comprised of one of three different disciplines within the sport: freestyle, alpine, and snowboard-cross. In recent years, the increased professionalism and substantial growth of snowboarding as a global sport has increasingly attracted the interest of exercise physiologists and sport scientists. Given the small (but growing) number of studies that have been published, the research analyzing the physiological and performance characteristics and requirements of snowboarding remains limited. The absence of such studies signifies a lack of examination into this important but under-explored area of research, which could contribute valuable information to the scientific community and international snowboarding teams. The studies conducted thus far have indicated different requirements of physiological and physical traits dependent upon the specific discipline of snowboarding in question. For example, in order to meet the divers demands of each discipline, athletes must develop various qualities, such as muscular strength and power. This can increase their ability to withstand the high forces and loads on the muscular system during competition, and further decrease their risk of lower limbs injuries. At the same time, the studies acknowledge the potential advantages of aerobic fitness in terms of recovery, to more efficiently sustain the athlete through both competitive and on- and off-snow training sessions. Given the value and breadth of application of these limited studies, further analysis and research could contribute greater knowledge and benefits to the field of snowboarding. Therefore, it is the purpose of this preliminary review to explore the current literature, providing further insight into the physiological and physical demands of snowboarding performance. This preliminary review is intended to stimulate interest among the communities of exercise physiologists, sport scientists and particularly coaches in order to improve our current understanding of snowboarding and its demands as a sport. This preliminary review further seeks to develop protocols and strategies to assess physiological and performance characteristics of snowboarding, monitor athletic performance, provide practical recommendations for training, identify new areas of scientific research, and develop accurate talent identification programs.

**Keywords: olympics, performance, physiological capabilities, test, training, snowboarding, winter sports**

OPEN ACCESS

***Edited by:***
*Martin Burtscher, University of Innsbruck, Austria*

***Reviewed by:***
*Thomas Haider, Universität Zürich, Switzerland*
*Klemens Mairer, University of Innsbruck, Austria*

***Correspondence:**
*Gianluca Vernillo*
*gianluca.vernillo@gmail.com*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *12 March 2018*
***Accepted:*** *01 June 2018*
***Published:*** *20 June 2018*

***Citation:***
*Vernillo G, Pisoni C and Thiébat G (2018) Physiological and Physical Profile of Snowboarding: A Preliminary Review. Front. Physiol. 9:770. doi: 10.3389/fphys.2018.00770*

## INTRODUCTION

Snowboarding in its current form began in the United States in the 1960s, and is now one of the most popular winter sports. In recognition of the trend, the International Olympic Committee officially introduced snowboarding into the Olympic program since Nagano 1998. Despite some decline over the last 10 years, snowboarding remains key among winter sports and is represented by a high number of participants at most alpine resorts worldwide (Bladin et al., 2004).

Traditionally, snowboarding is described as (i) freestyle (SBfs) - a skill-based discipline where athletes perform tricks and jumps either on the slopes or using specially built rails and half pipes; (ii) snowboard-cross (SBx) - where four to six athletes are required to maneuver inside a course characterized by multiple obstacles (e.g., banks and jumps); and (iii) alpine (SBalp) - where two athletes are required to ride simultaneously side-by-side down two parallel courses through gates with tight turns (Vernillo et al., 2016a).

Snowboarding as an athletic sport tests the boundaries of both physical and technical competence. The more we learn regarding the physiological demands placed upon elite snowboarders, the more effectively these qualities can be replicated and improved upon in the athletes. Knowledge of the muscular forces and energy systems involved in snowboarding is important for training prescription, performance enhancement, injury prevention and talent identification. However, for many years snowboarding studies have been limited to the realm of injuries [e.g., (Davidson and Laliotis, 1996; Machold et al., 2000; Langran and Selvaraj, 2002; Bladin et al., 2004; Torjussen and Bahr, 2005; Hasler et al., 2010; Bakken et al., 2011; Steenstrup et al., 2011; Ishimaru et al., 2012; Mahmood and Duggal, 2014; Schmitt and Muser, 2014; Wijdicks et al., 2014)] and biomechanical factors (Wu et al., 2006; Klous et al., 2010). More recently, snowboarding has attracted the interest of exercise physiologists and sport scientists, resulting in a small but growing number of studies being published. However, the extent of this research is based on the few available studies that analyze the physiological and performance requirements of snowboarding, and therefore limited information can be gleaned. We believe this is an important though neglected area of research, which could offer vital information to the scientific community as well as snowboarding teams throughout the globe. This preliminary review explores the current literature to provide insights into the physiological and physical characteristics of snowboarding performance. Our aim is to stimulate exercise physiologists, sport scientists and particularly coaches to improve their understanding of snowboarding demands in order to develop protocols and strategies to better assess physiological and performance characteristics of snowboarding, monitor snowboarders performance, provide practical recommendations for training as well as new areas of scientific research and develop accurate talent identification programs. Anthropometric variables and other factors that may be important in determining snowboarding performance are also discussed. Of note, the terms “snowboarders” and “snowboarding athletes” are frequently and interchangeably used throughout the following discussion, indicating the same population of athletes unless otherwise stated.

## PHYSIOLOGICAL AND PHYSICAL PROFILE OF SNOWBOARDING

### Anthropometric Characteristics

Several studies describe the anthropometric variables present in elite snowboarders (**Table 1**). The mean height is between 165.7 cm and 183.4 cm. The average body mass of elite men Italian snowboarders was 76.0 ± 9.7 kg (Vernillo et al., 2016b). This value is similar to that reported in a study of elite Austrian men snowboarders (75.4 ± 9.9 kg) (Platzer et al., 2009). Gathercole et al. (2015) reported that the average body mass of men and women Canadian SBx athletes was ∼86 kg and 64 kg, respectively. Body composition seems to be of similar import. Indeed, the average body fat percentage has been reported to be between 12 and 14% in elite men Italian snowboarders (Vernillo et al., 2016a). Taken together, these data argue for the potential importance of physique (as well as body composition) for snowboarding performance. Indeed, these characteristics may serve to manage the demands arising from fast and responsive turns and changing edges as well as negotiating obstacles. However, studies have incorporated only a small selection of anthropometric variables as part of investigations undertaken with different aims. Therefore, a more comprehensive data set on the anthropometric characteristics of elite snowboarders is missing and its quantification should be further investigated. In doing so, opportunities may arise to better identify anthropometric qualities key to snowboarding performance.

### Aerobic Fitness

Maximum oxygen uptake ($\dot{V}O_{2max}$) represents an accurate index of the integrated function of respiratory, cardiovascular, and muscular systems during exercise. Its importance for endurance performances is well and broadly established (Bassett and Howley, 2000). Within the literature, only two reports of aerobic fitness in elite snowboarders (**Table 1**) have been published thus far. The analysis of these reports showed $\dot{V}O_{2max}$ of ∼50 $mLO_2 \cdot kg^{-1} \cdot min^{-1}$ with a mean aerobic peak power output ranging from 3.5 to 5.3 $W \cdot kg^{-1}$. To the best of our knowledge, there are no other studies on aerobic characteristics of elite snowboarders. However, the importance of $\dot{V}O_{2max}$ as a determinant factor of success in snowboarding has been called into question. This skepticism can be attributed to a study showing that $\dot{V}O_{2max}$ was unrelated to the performance level of snowboarders (Vernillo et al., 2016a). This conclusion contradicts the findings of Neumayr et al. (2003), who reported one of the crucial factors to determine success in professional alpine skiing was high levels of aerobic power. However, it must also be acknowledged that the importance of $\dot{V}O_{2max}$ as a determining factor in alpine skiing has been similarly questioned (Maffiuletti et al., 2006) since $\dot{V}O_{2max}$ did not discriminate

**TABLE 1 |** Maximum oxygen uptake ($\dot{V}O_{2max}$) and anthropometric characteristics of snowboarders reported in the literature.

| Study (year) | Competitive level | Discipline | Sample size | Height (cm) | Body mass (kg) | Body fat (%) | $\dot{V}O_{2max}$ ($mLO_2 \cdot kg^{-1} \cdot min^{-1}$) | Mean aerobic power ($W \cdot kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Platzer et al., 2009 | Elite | – | 16 (women) | 167 ± 5 | 59.7 ± 5.3 | – | – | range: 3.5–4.7 |
| | | | 21 (men) | 177 ± 6 | 75.4 ± 9.9 | – | – | range: 3.8–5.3 |
| Gathercole et al., 2015 | Elite | SBx | 3 (women) | 165.7 ± 4.4 | 64.4 ± 4.5 | – | – | – |
| | | | 4 (men) | 183.4 ± 3.8 | 86.2 ± 3.4 | – | – | – |
| Vernillo et al., 2016a | Elite | SBx | 10 (men) | 181.0 ± 4.9 | 77.2 ± 9.2 | 11.9 ± 3.5 | 51.2 ± 4.5 | 4.5 ± 0.3 |
| | | SBalp | 10 (men) | 178.4 ± 9.8 | 78.1 ± 12.1 | 13.8 ± 3.7 | 49.7 ± 3.8 | 4.6 ± 0.5 |
| Vernillo et al., 2016b | Elite | SBfs | 10 (men) | 178.4 ± 7.9 | 72.8 ± 9.7 | – | – | – |
| | | SBx | 11 (men) | 181.7 ± 5.3 | 77.5 ± 8.8 | – | – | – |
| | | SBalp | 12 (men) | 178.7 ± 8.7 | 77.4 ± 10.6 | – | – | – |
| | | | | | | | | – |
| Vernillo et al., 2017 | Elite | SBalp | 8 (2 women) | 178.4 ± 9.8 | 78.1 ± 12.1 | – | – | – |

*Unless specified otherwise, data are reported as mean ± standard deviation. SBfs (freestyle), SBx (snowboard-cross), SBalp (alpine).*

between skiers of different levels (Haymes and Dickinson, 1980; Brown and Wilkinson, 1983; White and Johnson, 1991; Impellizzeri et al., 2009). Given the singular study that found that $\dot{V}O_{2max}$ was not associated with success in snowboarding, further efforts are needed to confirm and corroborate such a conclusion. Yet even if this is confirmed, it remains unlikely that the aerobic system can be considered as a determinant factor for success in competitive snowboarding, as in alpine skiing. With regards to aerobic training, although there is no literature reviewing the influence of this specific component upon snowboarding performance, $\dot{V}O_{2max}$ (and aerobic fitness in general) has been emphasized for its role in recovery (rather than energy provision) as for alpine skiing (Maffiuletti et al., 2006; Turnbull et al., 2009). Indeed, an efficient aerobic system is essential for recovery between competition runs, as well as to sustain the overall competition and on- and off-snow training season. For example, heart rate is a valid and reliable tool to monitor exercise intensity (Achten and Jeukendrup, 2003), even in snowboarding (Sporer et al., 2012). Accordingly, it has been used to determine the exercise intensity of training sessions. Kipp (1998) observed an average heart rate of 92% of predicted maximum heart rate during a halfpipe run in three elite American SBfs athletes. Arruza et al. (2005) used a manipulated training environment to examine the relationship between perceived fatigue and heart rate of five elite Spanish SBfs athletes. They reported that training demand was significantly related to heart rate ($r$ = 0.74). Of note, on a daily on-snow training session SBalp athletes displayed high work loads relative to their individual fitness, maintaining a mean heart rate of ∼75–80% of the maximum heart rate (Vernillo et al., 2016a). In summary, the available data suggests that performance in snowboarding is not significantly determined by aerobic fitness, though the potential advantages of aerobic fitness for snowboarders in terms of training and recovery should be acknowledged.

## Muscular Strength and Power

Elite snowboarders present significant leg strength values, as shown in **Table 2**. Anecdotally, it seems that there are no strength differences among the different snowboarding disciplines. However, there has yet to be any investigation into the potential differences in trunk and upper limb muscular strength. As for alpine skiing (Hintermeister et al., 1995, 1997; Berg and Eiken, 1999), in snowboarding the load on the muscle system can be directly influenced by the accelerative force, relative to body weight, and the velocity of the snowboarder. Muscular strength and power in snowboarders have primarily been measured on the lower limb muscles, particularly the quadriceps. This is probably because injuries (especially those involving the knee) are common in elite snowboarding (Torjussen and Bahr, 2005; Bakken et al., 2011). Therefore, insufficient quadriceps muscle strength may limit the snowboarders' ability to withstand the high forces and loads on the muscle system during snowboarding competitions, also increasing the risk of injuries. Additionally, preliminary evidence suggests a contribution from the lower leg muscles to the overall forces applied during snowboarding (Falda-Buscaiot and Hintzy, 2015). It seems then that possessing greater strength and endurance in the legs would be advantageous in snowboarding. Much of the current strength literature in snowboarding descriptively describes the general strength capacity of snowboarders. One exception comes from Gathercole et al.'s (2015) work with elite Canadian SBx athletes, where they investigate the feasibility of the counter movement jump test to examine the effect of both acute fatigue and training-induced adaptations. In general, little attention has been paid to the strength requirements of single- or multiple-day training/race. Therefore, studies clarifying the influence of strength training on the physiological response to snowboarding, and investigating the potential positive effects of strength training on snowboarding performance are necessary.

**TABLE 2** | Strength, power and jumping ability in snowboarders reported in the literature.

| Study (year) | Competitive level | Discipline | Sample size | Isometric quadriceps force (N) | Leg press power (W·kg$^{-1}$) | Jumping height (cm) | | Jumping power (W·kg$^{-1}$) | | Jumping force (N·kg$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | CMJ | SJ | CMJ | SJ | CMJ | SJ |
| Platzer et al., 2009 | Elite | – | 16 (women) | – | range: 4.46–6.54 | range: 23.0–37.3 | – | – | – | – | – |
| | | | 21 (men) | – | range: 5.42–7.69 | range: 32.5–48.9 | – | – | – | – | – |
| Gathercole et al., 2015 | Elite | SBx | 5 (3 women) | – | – | 45 ± 9 | – | 53.9 ± 5.5 | – | 20.7 ± 2.3 | – |
| Vernillo et al., 2016a | Elite | SBx | 10 (men) | 680.1 ± 76.8 | – | – | – | 71.6 ± 3.1 | 68.5 ± 7.4 | – | – |
| | | SBalp | 10 (men) | 731.9 ± 181.9 | – | – | – | 73.0 ± 3.7 | 70.6 ± 7.3 | – | – |
| Vernillo et al., 2016b | Elite | SBfs | 10 (men) | 684.6 ± 137.2 | – | – | – | – | – | 26.8 ± 2.8 | – |
| | | SBx | 11 (men) | 674.1 ± 78.8 | – | – | – | – | – | 26.2 ± 2.8 | – |
| | | SBalp | 12 (men) | 754.6 ± 162.1 | – | – | – | – | – | 27.1 ± 3.4 | – |

*Unless specified otherwise, data are reported as mean ± standard deviation. SBfs (freestyle), SBx (snowboard-cross), SBalp (alpine).*

## Strength Asymmetry

Strength asymmetry refers to the relative difference between legs in maximal force capacity. Its quantification can be useful in identifying athletes at increased risk of incurring lower-limb musculoskeletal injuries (Impellizzeri et al., 2007). Due to an asymmetrical position on the board [with the left or right leg in front (regular or goofy position, respectively)], snowboarders can be at risk of developing strength asymmetry between the two legs. We have recently published data tested this hypothesis (**Figure 1**) (Vernillo et al., 2016b), where the strength asymmetry of 33 elite snowboarders [SBfs ($n$ = 10), SBx ($n$ = 11) and SBalp ($n$ = 12)] was assessed. All athletes underwent tests with the same protocol, consisting of an isometric maximal voluntary contraction of both the front and rear leg, and a vertical jump test on a portable force platform [with asymmetry measured by a parallel wooden platform leveled with the force platform (Impellizzeri et al., 2007)]. Only SBalp athletes presented a ∼10.5% strength asymmetry, favoring the rear leg (**Figure 1**). This likely occurs due to greater weight distribution on the rear leg during snowboarding that could reflect an increased adaptation of muscle characteristics, such as size and volume. We confirmed this hypothesis observing a ∼14% difference in muscle architecture between the front and the rear leg (i.e., a lower pennation angle associated with a greater fascicle length), which also suggests the presence of a morphological asymmetry in elite SBalp athletes (Vernillo et al., 2017). In summary, it appears that functional and morphological asymmetries are only present in SBalp. A cut-off of ± 15% is commonly accepted as being clinically relevant in relation to developing a potential harmful strength asymmetry (Impellizzeri et al., 2007; Schmitt et al., 2012). However, whether such asymmetry represents a potential risk factor for injury, or an intrinsic characteristic remains a point of ongoing debate. This is because strength asymmetry can also be considered a peculiarity of many sports due to a constant training overload on the dominant limb. Therefore, strength asymmetry in snowboarders should be taken into consideration in terms of predisposition to lower limbs musculoskeletal injuries. It should further be acknowledged as practically relevant on the assessment of functional muscular deficits consequent to injury as well as exercise prescription. Given the beneficial (but limited) data acquired thus far, further studies that include athletes of more varying attributes and backgrounds within snowboarding could potentially yield more generalized results.

# THE RELATIONSHIP BETWEEN PHYSIOLOGICAL TESTS AND SNOWBOARDING PERFORMANCE

Snowboarding is comprised of various disciplines that may differ in their physiological and technical requirements. Accordingly, success in snowboarding may be related to a complex interaction of multiple variables. For example, SBx and SBalp performances are positively related both to body dimension and relative body composition (Vernillo et al., 2016a). However, it should

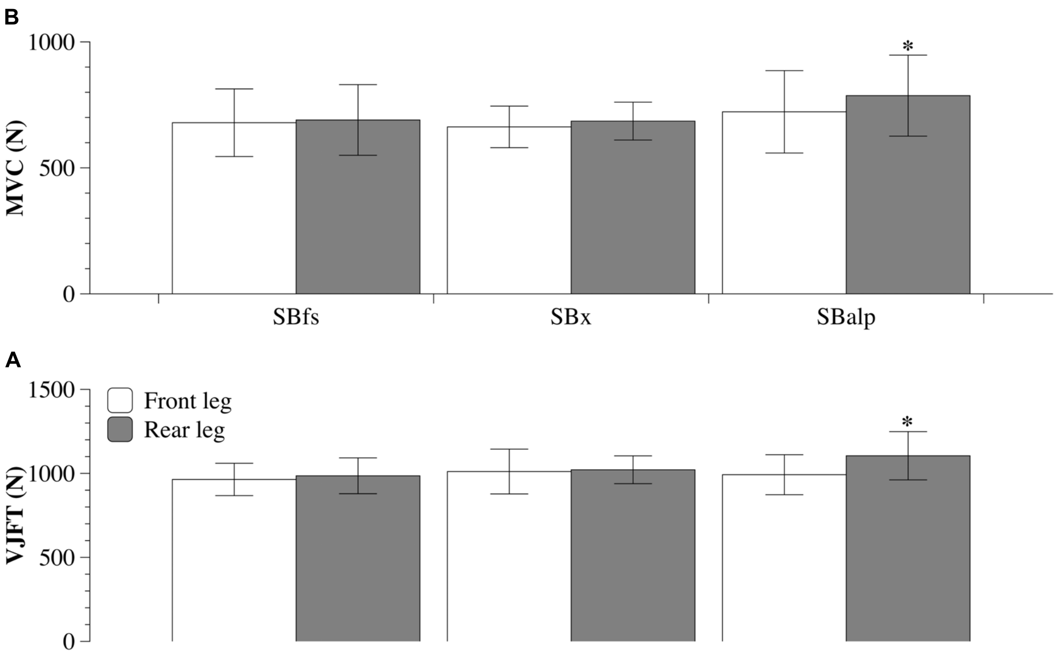


**FIGURE 1 |** Mean ± standard deviation of the results from the isometric maximal voluntary contraction test (MVC, **A**) and the vertical jump force test (VJFT, **B**) in elite Italian snowboarders. Based on data from Vernillo et al. (2016b). *Significantly different from the front leg ($P < 0.001$). SBfs (freestyle), SBx (snowboard-cross), SBalp (alpine).

be stressed that (to date) only the above-mentioned study has sought to measure anthropometric variables and correlate them with indices of snowboarding performance. This was largely descriptive and done with relatively small sample sizes. Thus far, no snowboarding specific training interventions (or comparison with non-snowboarding control groups) have been conducted. In addition, more specific physical characteristics of snowboarders (such as the somatotype distribution) have not yet been tested. Therefore, the relation between percentage body fat and other measures of body dimensions with snowboarding performance is yet to be clearly established. Recent data on elite men Italian snowboarders showed that $\dot{V}O_{2max}$ (as well as the ventilatory thresholds) was not correlated with performance (Vernillo et al., 2016a). In contrast, absolute and relative power output assessed during incremental cycling tests seem to be more important in determining snowboarding performance. As reported by Platzer et al. (2009), peak power output (normalized for body mass) was strongly related to success among women snowboarders ($r$ = 0.85). This observation was confirmed and extended by Vernillo et al. (2016a), reporting that absolute and normalized power outputs (as well as power output at the first and second ventilatory threshold) were strongly related to men SBx and SBalp performances ($r$ = −0.84 to −0.93). To date, these are the only studies that have sought to compare snowboarding performance with aerobic-measured cycle ergometer values. Taken together, these results highlight that power output seems to represent a greater indicative value of the snowboarding performance than do ventilatory responses. This suggests that muscle power is a better predictor of snowboarding performance than, for example, $\dot{V}O_{2max}$. Finally, early research found muscular power (measured by isokinetic leg press) to be strongly correlated to snowboarding superiority among Austrian snowboarding team members (Platzer et al., 2009). Vernillo et al. (2016a) confirmed and extended the previous observations, reporting isometric muscle strength at the quadriceps to be strongly related to men SBx and SBalp performances ($r$ = −0.93 to −0.97). Therefore, muscle strength and power are important determinants in snowboarding competition. Indeed, high values of these parameters may allow the snowboarders to train/compete at a reduced percentage of their maximal strength/power, thereby reducing the metabolic consequences of sustained muscular activities, and to withstand the high forces of snowboarding. A strong association has also been found between leg stiffness [measured form flight and contact times during multi-rebound jumps (Dalleau et al., 2004)] and men SBx and SBalp performances ($r$ = −0.85 to −0.89) (Vernillo et al., 2016a), highlighting the important role of muscular stiffness regulation to maintain the muscle force generating capacity. Of interest, the ability to generate explosive strength (e.g., peak power determined during counter movement jumps) was not significantly correlated to indexes of snowboarding performance (Platzer et al., 2009; Vernillo et al., 2016a), displaying that snowboarding, as alpine skiing, should not be considered an "explosive" sport. Despite this conclusion, the functional significance of counter movement jump must be acknowledged. For example, while studying elite Canadian SBx athletes, Gathercole et al. (2015) observed counter movement jumps to be a suitable monitoring tool for the detection of both acute fatigue and training-induced adaptations. Factors such as technical ability as well as trunk and upper body muscle strength might also influence the athletes' capacity to withstand the forces generated during snowboarding, and further serve to generate speed. Such components may prove invaluable when combine with the physiological assessment of snowboarders in the pursuit of future studies.

## Determinants of Snowboarding Performance

In the study of 37 elite Austrian snowboarders (21 men; 16 women), Platzer et al. (2009) address the key determinants of snowboarding performance. Variables for each participant included anthropometric measures (height and body mass) as well as physiological and functional markers (aerobic peak power output, leg and core power, stability index, bench press/pull strength and maximum push off speed on an indoor start simulator). Using a multiple regression analysis, it was shown that the variables considered explained 61 and 73% of the variance of WC points in women and men, respectively. Examining the different disciplines, the same variables explained 61 and 98% of the variance of FIS points in women's SBalp and SBx events, respectively, as well as 78% of variance of FIS points in men's SBfs halfpipe events. It was concluded that anthropometric, physiological and functional variables are a good predictor for snowboard performance in women but not for men, arguing that other performance-determining variables (e.g., psychological, equipment and coordination) might play a role on influencing the snowboard performance.

# CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Contemporary snowboarding literature describes the physiological and performance characteristics of snowboarders. As we have highlighted throughout this preliminary review, important gaps in our physiological and performance knowledge of snowboarding still exist. The determinants of snowboarding performance remain unclear, but may be attributed to a variety of trainable variables. Improvement of performance analysis within snowboarding is therefore required to better understand the internal and external loads experienced by this population of athletes. Without implementing such methods, practitioners lack a specific understanding of the sport regarding the workloads, durations and stress involved. Therefore, they would be limited to speculate on training requirements for these athletes. Ideal training regimens to optimize physiological markers and snowboarding performance have not yet been identified. Accordingly, well-designed training studies are needed to confirm the indications presented in this preliminary review. Quantifications of physiological and physical requirements of one (or several days) of training and races are needed in order to optimize athletic performance. There remains a need to provide snowboarders' physiological and physical profiles that are not biased by a nation-specific training methodology. An increase in research of snowboarding could positively benefit the overall level of professionalism within the sport. Until further research is conducted, snowboarding provides an ongoing challenge for exercise physiologists, sport scientists, and conditioning experts alike in building accurate and structured training regimes. We hope this preliminary review will promote further research in all the aspects highlighted in it.

# AUTHOR CONTRIBUTIONS

GV, CP, and GT conceived and designed the research, analyzed the data, prepared the figure, drafted the manuscript, edited and revised the manuscript, and approved the final version of the manuscript.

# FUNDING

No support was provided for this study by any manufacturer of the instruments used.

# ACKNOWLEDGMENTS

We thank Luigi Devizzi, Giacomo Kratter, Luca Migliorini, Matteo Pirletti, Luca Pozzolini, Stefano Pozzolini, Erich Pramsohler, and Frederich Tropiano as well as all the athletes for their help in the collection of our published data. We also extend our gratitude to the Italian Winter Sports Federation for its support. Finally, we thank Hayley L. Patmore for her assistance in English proof reading.

# REFERENCES

Achten, J., and Jeukendrup, A. E. (2003). Heart rate monitoring: applications and limitations. *Sports Med.* 33, 517–538.

Arruza, J. A., Telletxea, S., Azurza, A., Balague, G., and Brustad, R. J. (2005). Physiological and psychological indicators in the evaluation of the work capacity of snowboarders. *J. Sport Behav.* 28, 125–135.

Bakken, A., Bere, T., Bahr, R., Kristianslund, E., and Nordsletten, L. (2011). Mechanisms of injuries in World Cup Snowboard Cross: a systematic video analysis of 19 cases. *Br. J. Sports Med.* 45, 1315–1322. doi: 10.1136/bjsports-2011-090527

Bassett, D. R. Jr., and Howley, E. T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med. Sci. Sports Exerc.* 32, 70–84.

Berg, H. E., and Eiken, O. (1999). Muscle control in elite alpine skiing. *Med. Sci. Sports Exerc.* 31, 1065–1067.

Bladin, C., McCrory, P., and Pogorzelski, A. (2004). Snowboarding injuries: current trends and future directions. *Sports Med.* 34, 133–139.

Brown, S. L., and Wilkinson, J. G. (1983). Characteristics of national, divisional, and club male alpine ski racers. *Med. Sci. Sports Exerc.* 15, 491–495.

Dalleau, G., Belli, A., Viale, F., Lacour, J. R., and Bourdin, M. A. (2004). simple method for field measurements of leg stiffness in hopping. *Int. J. Sports Med.* 25, 170–176.

Davidson, T. M., and Laliotis, A. T. (1996). Snowboarding injuries, a four-year study with comparison with alpine ski injuries. *West. J. Med.* 164, 231–237.

Falda-Buscaiot, T., and Hintzy, F. (2015). Comparison of muscle activation pattern between alpine skiing and snowboarding. *Comput. Methods Biomech. Biomed. Engin.* 18, 1936–1937.

Gathercole, R. J., Stellingwerff, T., and Sporer, B. C. (2015). Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *J. Strength Cond. Res.* 29, 37–46. doi: 10.1519/JSC.0000000000000622

Hasler, R. M., Berov, S., Benneker, L., Dubler, S., Spycher, J., Heim, D., et al. (2010). Are there risk factors for snowboard injuries? A case-control multicentre study of 559 snowboarders. *Br. J. Sports Med.* 44, 816–821. doi: 10.1136/bjsm.2010.071357

Haymes, E. M., and Dickinson, A. L. (1980). Characteristics of elite male and female ski racers. *Med. Sci. Sports Exerc.* 12, 153–158.

Hintermeister, R. A., O'Connor, D. D., Dillman, C. J., Suplizio, C. L., Lange, G. W., and Steadman, J. R. (1995). Muscle activity in slalom and giant slalom skiing. *Med. Sci. Sports Exerc.* 27, 315–322.

Hintermeister, R. A., O'Connor, D. D., Lange, G. W., Dillman, C. J., and Steadman, J. R. (1997). Muscle activity in wedge, parallel, and giant slalom skiing. *Med. Sci. Sports Exerc.* 29, 548–553.

Impellizzeri, F. M., Rampinini, E., Freschi, M., Maffiuletti, N. A., Bizzini, M., and Mognoni, P. (2009). "Identification of the physical characteristics that discriminate between competitive levels and specialities of alpine skiers," in *Science and Skiing IV*, eds E. Muller, S. Lindinger, and T. Stöggl (Aachen: Meyer & Meyer Sport), 272–280.

Impellizzeri, F. M., Rampinini, E., Maffiuletti, N., and Marcora, S. M. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Med. Sci. Sports Exerc.* 39, 2044–2050.

Ishimaru, D., Ogawa, H., Wakahara, K., Sumi, H., Sumi, Y., and Shimizu, K. (2012). Hip pads reduce the overall risk of injuries in recreational snowboarders. *Br. J. Sports Med.* 46, 1055–1058. doi: 10.1136/bjsports-2012-091204

Kipp, R. W. (1998). Physiological analysis and training for snowboard's halfpipe event. *Strength Cond.* 20, 8–13.

Klous, M., Muller, E., and Schwameder, H. (2010). Collecting kinematic data on a ski/snowboard track with panning, tilting, and zooming cameras: is there sufficient accuracy for a biomechanical analysis? *J. Sports Sci.* 28, 1345–1353. doi: 10.1080/02640414.2010.507253

Langran, M., and Selvaraj, S. (2002). Snow sports injuries in Scotland: a case-control study. *Br. J. Sports Med.* 36, 135–140.

Machold, W., Kwasny, O., Gassler, P., Kolonja, A., Reddy, B., Bauer, E., et al. (2000). Risk of injury through snowboarding. *J. Trauma* 48, 1109–1114.

Maffiuletti, N. A., Impellizzeri, F., Rampinini, E., Bizzini, M., and Mognoni, P. (2006). Is aerobic power really critical for success in alpine skiing? *Int. J. Sports Med.* 27, 166–167. ; author reply 168-169,

Mahmood, B., and Duggal, N. (2014). Lower extremity injuries in snowboarders. *Am. J. Orthop. (Belle Mead NJ).* 43, 502–505.

Neumayr, G., Hoertnagl, H., Pfister, R., Koller, A., Eibl, G., and Raas, E. (2003). Physical and physiological factors associated with success in professional alpine skiing. *Int. J. Sports Med.* 24, 571–575.

Platzer, H. P., Raschner, C., Patterson, C., and Lembert, S. (2009). Comparison of physical characteristics and performance among elite snowboarders. *J. Strength Cond. Res.* 23, 1427–1432. doi: 10.1519/JSC.0b013e3181aa1d9f

Schmitt, K. U., and Muser, M. (2014). Investigating reaction times and stopping performance of skiers and snowboarders. *Eur. J. Sport Sci.* 14(Suppl. 1), S165–S170. doi: 10.1080/17461391.2012.666267

Schmitt, L. C., Paterno, M. V., and Hewett, T. E. (2012). The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J. Orthop. Sports Phys. Ther.* 42, 750–759. doi: 10.2519/jospt.2012.4194

Sporer, B. C., Cote, A., and Sleivert, G. (2012). Warm-up practices in elite snowboard athletes. *Int. J. Sports Physiol. Perform.* 7, 295–297.

Steenstrup, S. E., Bere, T., Florenes, T. W., Bahr, R., and Nordsletten, L. (2011). Injury incidence in qualification runs versus final runs in FIS World Cup snowboard cross and ski cross. *Br. J. Sports Med.* 45, 1310–1314. doi: 10.1136/bjsports-2011-090528

Torjussen, J., and Bahr, R. (2005). Injuries among competitive snowboarders at the national elite level. *Am. J. Sports Med.* 33, 370–377.

Turnbull, J. R., Kilding, A. E., and Keogh, J. W. (2009). Physiology of alpine skiing. *Scand. J. Med. Sci. Sports* 19, 146–155. doi: 10.1111/j.1600-0838.2009.00901.x

Vernillo, G., Pisoni, C., Sconfienza, L. M., Thiebat, G., and Longo, S. (2017). Changes in muscle architecture of vastus lateralis muscle after an alpine snowboarding race. *J. Strength Cond. Res.* 31, 254–259. doi: 10.1519/JSC.0000000000001469

Vernillo, G., Pisoni, C., and Thiebat, G. (2016a). Physiological characteristics of elite snowboarders. *J. Sports Med. Phys. Fitness* 56, 527–533.

Vernillo, G., Pisoni, C., and Thiebat, G. (2016b). Strength asymmetry between front and rear leg in elite snowboard athletes. *Clin. J. Sport Med.* 26, 83–85. doi: 10.1097/JSM.0000000000000194

White, A. T., and Johnson, S. C. (1991). Physiological comparison of international, national and regional alpine skiers. *Int. J. Sports Med.* 12, 374–378.

Wijdicks, C. A., Rosenbach, B. S., Flanagan, T. R., Bower, G. E., Newman, K. E., Clanton, T. O., et al. (2014). Injuries in elite and recreational snowboarders. *Br. J. Sports Med.* 48, 11–17. doi: 10.1136/bjsports-2013-093019

Wu, Q., Igci, Y., Andreopoulos, Y., and Weinbaum, S. (2006). Lift mechanics of downhill skiing and snowboarding. *Med. Sci. Sports Exerc.* 38, 1132–1146.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer KM and handling Editor declared their shared affiliation.

frontiers in Physiology

BRIEF RESEARCH REPORT
published: 31 July 2018
doi: 10.3389/fphys.2018.01032

# Slipstreaming in Gravity Powered Sports: Application to Racing Strategy in Ski Cross

*Franz Konstantin Fuss**

*Smart Equipment Engineering and Wearable Technology Research Program, Centre for Design Innovation, Swinburne University of Technology, Melbourne, VIC, Australia*

The principles of slipstreaming or drafting are very well known in muscle-powered sports, but unknown in gravity-powered sports. Typical examples of gravity-powered sports, where several athletes are racing against each other, are ski-cross and snowboard-cross. The aim of this research is to investigate the effectiveness and practical applicability of slipstreaming in ski-cross. A glide model consisting of leading and trailing skiers was developed and used with existing aerodynamic drag and lift data sets from wind tunnel tests. Different scenarios were tested as to their effect on slipstreaming, such as variation of speed, skiers' mass, slope angle, air density, and racing posture (high/low tucked position). The higher the trailing skier's inertial force and acceleration is compared to the leading one, the quicker the trailing skier can catch up. Making more ground up on the racing track is related to higher speed, less body mass (of both skiers), flatter slope angle, denser air, and higher racing posture (high tucked position of both skiers). The glide model presented in this research can be used in the future for testing of slope track design, provided that precise dimensions of terrain features are available.

**Keywords: sports engineering, aerodynamics, ski cross, slipstreaming, drafting, glide model, drag, lift**

OPEN ACCESS

***Edited by:***
*Gianluca Vernillo,*
*Università degli Studi di Milano, Italy*

***Reviewed by:***
*Andrea Zignoli,*
*Università degli Studi di Verona, Italy*
*Andrew Renfree,*
*University of Worcester,*
*United Kingdom*

***Correspondence:***
*Franz Konstantin Fuss*
*fkfuss@swin.edu.au*

***Specialty section:***
*This article was submitted to Exercise Physiology, a section of the journal Frontiers in Physiology*

***Received:*** *26 April 2018*
***Accepted:*** *11 July 2018*
***Published:*** *31 July 2018*

***Citation:***
*Fuss FK (2018) Slipstreaming in Gravity Powered Sports: Application to Racing Strategy in Ski Cross. Front. Physiol. 9:1032. doi: 10.3389/fphys.2018.01032*

## INTRODUCTION

Slipstreaming or drafting is a commonly used strategy in sports, specifically in cycling (Barry et al., 2014, 2015), speed skating (Rundell, 1996), running (Pitcher, 2009), wheelchair racing, and other sports. These sports disciplines, however, are muscle-powered, where slipstreaming reduces energetic demands. There is no single study on gravity-powered sports, probably because there is often only one athlete or team on the track rather than directly competing against each other. Classical gravity-powered sports are bobsleigh (after the start phase), luge (after the start phase), skeleton, alpine skiing, ski jumping, and snowboarding. However, in 2006 and 2010 respectively, snowboard-cross and ski-cross became Olympic disciplines, where 4–6 athletes are racing against each other on the same track. Although there is no judged component, these disciplines are still considered freestyle because of terrain features typical for freestyle. Baggy and fluttering clothing is another freestyle feature, actually prescribed by the ski cross rules (FIS, 2017, rule 4511.6 Suit Measurement). Yet, as in alpine skiing, speed is crucial and the first athlete that crosses the finish line wins, which in turn requires obeying aerodynamics principles.

Slipstreaming is governed by interference drag (Hoerner, 1965). When two bluff bodies are aligned in series in the free airstream, the drag force on the trailing body decreases as the bodies get closer. There is also an effect on the leading body with a slight reduction of drag.

Fuss (2011) investigated the drag forces on trailing and leading skiers with wind tunnel tests, and the results followed the expected principles of bluff-body interference drag, as outlined by Hoerner (1965). It is, however, unknown, whether these results are practically effective in gravity-powered sports. In contrast to muscle-powered sports, slipstreaming in gravity-powered sports is not applicable to saving the athlete's muscle power (required for propulsion) but should rather influence the trailing skier by catching up with the leading one, i.e., closing the distance between two athletes racing downhill back to back. This is all the more important in ski- and snowboard cross, as often only 10–20 cm determine a win.

The aim of this study is to derive a strategy for slipstreaming in ski-cross from a glide model, and provide advice and practical recommendations for athletes.

## METHODOLOGY

The method consists of the following procedures:

(1) establishing functions of aerodynamic drag and lift with respect to the distance between leading and trailing skiers from existing data sets (Fuss, 2011);
(2) develop a glide model that returns speed and distance glided; and
(3) testing the numerical version of the model with two skiers and different parameters in order to understand the dynamics of slipstreaming (e.g., is slipstreaming more efficient at a high or low tucked position?).

In order to assess how the distance between two skiers changes when racing the following pre-requisites are required:

(1) aerodynamic drag and lift areas ($Ad$ and $Al$) of the trailing skier as a function of distance $D$ between two skiers;
(2) aerodynamic drag and lift areas of the leading skier as a function of distance $D$ between two skiers;
(3) a mathematical glide model.

$Ad$ and $Al$ are the drag and lift coefficients ($C_D$ and $C_L$) multiplied by the projected areas $A$, and calculated from

$$F_D = \frac{\rho C_D A v^2}{2} \rightarrow C_D A = Ad = \frac{2F_D}{\rho v^2} \tag{1}$$

$$F_L = \frac{\rho C_L A v^2}{2} \rightarrow C_L A = Al = \frac{2F_L}{\rho v^2} \tag{2}$$

where $F_D$ and $F_L$ are drag and lift forces, $v$ is the free-stream velocity, and $\rho$ is the air density.

For establishing the functions of $Ad$ and $Al$ against distance $D$, the data of Fuss (2011) were fit with different functions. In addition to the data of Fuss (2011), extreme data were included in the dataset that helped establish the correct asymptotic values of the fit functions in absence of measurement data. These extreme values were:

- leading skier: at $D = 0$, $Ad = Ad_{\max}$ and $Al = Al_{\max}$, as the interference drag and lift on the leading body returns to the original single-body drag and lift if the distance $D$ closes to zero. This is only of theoretical importance in skiing, however, essential for correct modeling. When plotting $D$ on a logarithmic scale, then $Ad$ and $Al$ asymptote to $Ad_{\max}$ and $Al_{\max}$ as $D$ approaches 0.
- trailing skier: at $D = 0$, $Ad = 0$ and $Al = 0$, as the trailing body does not experience any drag after having merged with the leading body.
- trailing and leading skiers: at $D = \infty$, $Ad = Ad_{\max}$ and $Al = Al_{\max}$, as the interference drag vanishes at large $D$; practically, no interference drag is expected at $D = 100$ m, which means that the asymptotic value should have been reached at $D = 100$ m.

The following fit functions were used:

- $Ad$ of leading skier: fitted by a negative Gaussian function of the decadic logarithm of $D$ ($y = a–be^{(\log x-c)/d}$; where $a = Ad_{\max}$; **Figure 1A**). The Gaussian function also provides identical asymptotic $Ad$ values for small and large distances (decadic logarithm of $D$; **Figure 1B**);
- $Al$ of leading skier: fitted by an average fit (constant $Al$) as this parameter was not affected by the distance $D$. (**Figure 1A**);
- $Ad$ and $Al$ of trailing skier: exponential functions of the form $y = a+be^{-c/x}$ (where $a = 0$), as drag and lift asymptote to their maximum values at large distances and to zero at very small distances (**Figure 1C**).

Care was taken that the asymptotic $Ad$ and $Al$ values were the same for both leading and trailing skiers. This was required for the first modeling step. The data shown in **Figure 1** refer to distances of $D = 2$, 3, 4, 5.5, and 7 m. The unequal spacing of these data (1 m and 1.5 m increments) does not substantially influence the fit results. When taking the $Ad$ and $Al$ data of $D = 5.5$ and using them at hypothetical $D$ of 5 and 6 m (instead of 5.5 m), then the fit deviates on average only by 0.09% of $Ad_{\max}$ of the trailing skier, by 0.40% of $Al_{\max}$ of the trailing skier, and by 0.03% of $Ad_{\max}$ of the leading skier.

The glide model was based on the free-body diagram of a skier gliding downhill, and all the forces acting on it (**Figure 1D**). Although glide models were already developed by Luethi and Denoth (1987; numerical), Broker (1991; inaccessible), and Nørstrud (2008a; 2008b with lengthy derivations), a straightforward analytical solution is presented subsequently.

The force equilibriums in $x$- and $y$-directions (**Figure 1D**) are:

$$F_{Gy} = F_R + F_L \tag{3}$$

$$F_{Gx} = F_I + F_F + F_D \tag{4}$$

where the $x$–coordinate of the coordinates system is parallel to the slope and pointing downhill and the $y$–coordinate is perpendicular to the slope pointing upwards and forwards; $F_{Gx}$ and $F_{Gy}$ are the $x$- and $y$-components of the gravitational force (skier plus gear); $F_R$ is the ground reaction force acting on the skis; $F_F$ is the friction force (uphill) acting on the skis; $F_I$ is the inertial force (uphill) opposite to the acceleration vector (downhill) acting on the skier; and $F_D$ and $F_L$ are drag- and lift-forces, acting on the skier in uphill and upward/forward direction, respectively.

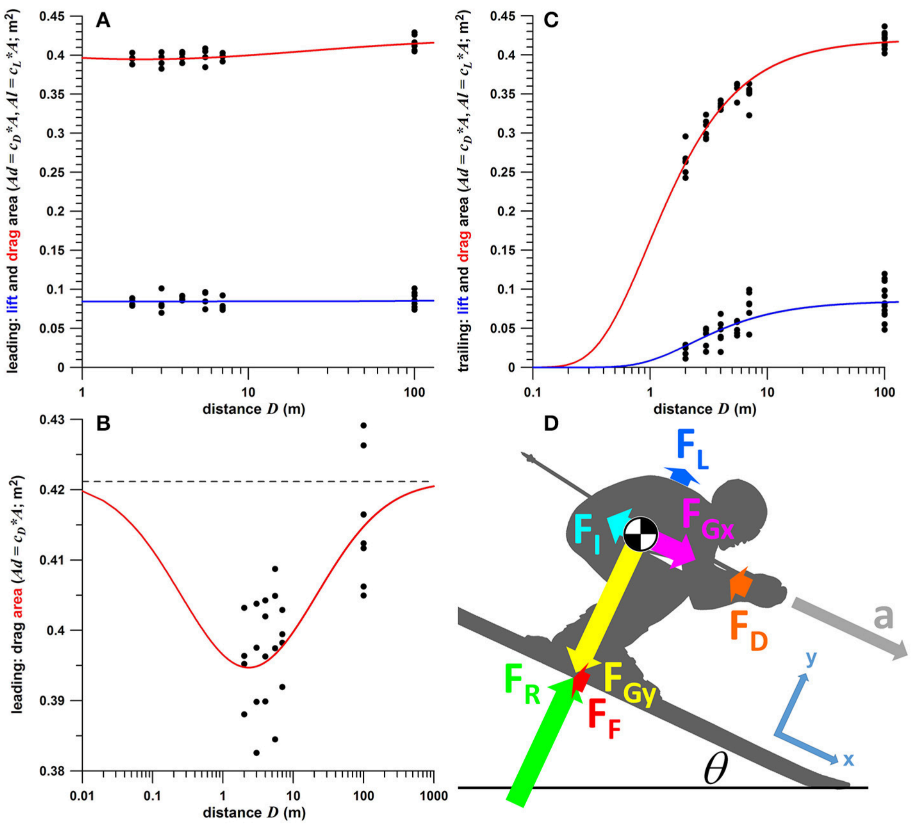


**FIGURE 1 | (A–C)** Drag and lift area, *Ad* and *Al* (coefficient of drag and lift times projected area) against distance between the two skiers (data from Fuss, 2011) including fit functions (red: drag area, blue: lift area); **(A)** leading skier; **(B)** enlarged graph of drag area of leading skier; **(C)** trailing skier; **(D)** free body diagram of a skier (the coordinate system of which is aligned to the slope), including vectors of acceleration ($a$) and forces ($F_D$ and $F_L$ are drag and lift forces; $F_{Gx}$ and $F_{Gy}$ are the $x$- and $y$-components of the gravitational force; $F_R$ is the ground reaction force acting on the skis; $F_F$ is the friction force acting on the skis; and $F_I$ is the inertial force); the relative size of the force vectors is true for a slope angle ($\theta$) of 25°, a mass of 100 kg (body plus gear), and a speed of 100 kph; ◐ = center of mass.

Solving Equation (3) for $F_R$, and substituting $\mu F_R = \mu \left(F_{Gy} - F_L\right)$ for $F_F$ in Equation (4) yields

$$F_I = F_{Gx} - \mu F_{Gy} + \mu F_L - F_D \tag{5}$$

where $\mu$ is the kinetic coefficient of friction, resulting in

$$a\, m = g\, m \sin\theta - \mu\, g\, m \cos\theta + \mu F_L - F_D \tag{6}$$

where $a$ is the acceleration of the skier, $m$ is the mass of skier plus gear, $\theta$ is the slope angle (**Figure 1D**; $\theta$ is positive), and $g$ is the gravitational acceleration. The differential equation to be solved is

$$\begin{aligned}\frac{\mathrm{d}v}{\mathrm{d}t} &= \left(g \sin\theta - \mu g \cos\theta\right) + \frac{\mu}{m} F_L - \frac{1}{m} F_D \\ &= c_1 + \frac{\mu}{m}\frac{\rho Al}{2} v^2 - \frac{1}{m}\frac{\rho Ad}{2} v^2 = c_1 + c_3 v^2 - c_2 v^2\end{aligned} \tag{7}$$

where $c_1 = g \sin\theta - \mu g \cos\theta$ , $c_2 = 0.5\rho Ad/m$, and $c_3 = 0.5\rho Al\mu/m$.

After rearranging and defining $c_4 = c_2 - c_3$ (as $Ad > \mu Al$),

$$\frac{\mathrm{d}v}{\mathrm{d}t} = c_1 - c_4 v^2 \tag{8}$$

Solving for d$t$

$$\mathrm{d}t = \frac{1}{c_1 - c_4 v^2} dv \tag{9}$$

and integrating both sides

$$t_1 - t_0 = \int_{v_0}^{v_t} \frac{1}{c_1 - c_4 v^2} dv \tag{10}$$

where $t_0 = 0$. Solving the integral yields

$$t = \left[\frac{\tanh^{-1}\left(v\sqrt{\frac{c_4}{c_1}}\right)}{\sqrt{c_1 c_4}}\right]_{v_0}^{v_t} \tag{11}$$

and

$$t\sqrt{c_1 c_4} = \tanh^{-1}\left(v_t\sqrt{\frac{c_4}{c_1}}\right) - \tanh^{-1}\left(v_0\sqrt{\frac{c_4}{c_1}}\right) \tag{12}$$

Solving for $v_t$ yields

$$v_t = \sqrt{\frac{c_1}{c_4}} \tanh\left[\tanh^{-1}\left(v_0\sqrt{\frac{c_4}{c_1}}\right) + t\sqrt{c_1 c_4}\right] \tag{13}$$

i.e., the velocity as a function of time.

Simplifying Equation (13) by defining three further constants, $c_5 = \tanh^{-1}\left(v_0\sqrt{\frac{c_4}{c_1}}\right)$, $c_6 = \sqrt{c_1 c_4}$, and $c_7 = \sqrt{\frac{c_1}{c_4}}$, yields

$$v_t = c_7 \tanh(c_5 + c_6 t) \tag{14}$$

$c_7$ constitutes the terminal velocity $v_{term}$ where $a = 0$ and consequently $F_I = 0$, and $F_{Gx} = F_F + F_D$:

$$c_7 = v_{term} = \sqrt{\frac{c_1}{c_4}} = \sqrt{\frac{g sin\theta - \mu g \cos\theta}{c_2 - c_3}} = \sqrt{\left(\frac{2mg}{\rho}\right)\left(\frac{sin\theta - \mu \cos\theta}{Ad - \mu Al}\right)} \tag{15}$$

Reducing Equation (15) to large variables, by removing common constants and small variables (i.e., $Al$, as $Ad \approx 60\mu Al$), yields

$$v_{term} \propto \sqrt{\frac{m}{Ad}} \tag{16}$$

where the right part of Equation (16) is equivalent to the "*anthropometric code number*" by Luethi and Denoth (1987; who used $mg$ instead of $m$), explaining why heavier and smaller skiers are faster. The practical application of Equation (16) is, what every head coach should do, namely calculate this ratio, and compare and rank the team members. This method is also essential for drafting new team members. The data required for this ration are (1) the mass of the skier plus gear, and (2) $Ad$ and $Al$ either from wind tunnel tests or from glide tests by recording the speed with a ski speed meter (e.g., vLink™ by Advanced Racing Computers, Salt Lake City, UT, USA; Kirby, 2009). The data obtained from the speed meter at a realistic speed for different and defined tucked positions is the velocity as a function of time, which can be fitted with the function given in Equation (14), to obtain $Ad$, but also an estimate of $Al$ and $\mu$, if realistic fit boundaries are selected.

Integrating Equation (14) for calculating the displacement $x$ on the slope, for initial conditions of $t_0 = 0$ and $x_0 = 0$:

$$x_t = c_7 \int_{t_0}^{t_1} \tanh(c_5 + c_6 t)\, dt \tag{17}$$

yields

$$x_t = \frac{c_7}{c_6}\left\{\ln\left[\cosh(c_5 + c_6 t)\right] - \ln\left[\cosh(c_5)\right]\right\} \tag{18}$$

where ln denotes the natural logarithm. Solving Equation (18) for $t$ yields:

$$t_x = \frac{\cosh^{-1}\left\{e^{\frac{c_6}{c_7}x + \ln\left[\cosh(c_5)\right]}\right\} - c_5}{c_6} \tag{19}$$

There are two boundary conditions related to the derivation of the glide model equations. From Equation (11) it becomes evident that the constants $c_1$ and $c_4$ must be positive. Constant $c_4$ is larger than 0 by definition, as $Ad > \mu\ Al$. Solving $c_1 = g \sin\theta - \mu g \cos\theta$ for $\theta$ reveals that $\theta \geq \tan^{-1}\mu$ for $c_1 \geq 0$. If $\mu = 0.05$, then the critical slope angle would be 0.04996 rad which equals 2.862°. Therefore, how would slope angles smaller than 2.862° influence the glide model, if $c_1$ were smaller than 0, and so were the arguments of the square roots of constants $c_5$, $c_6$, and $c_7$? The answer is given by the equation of $c_5$: the argument of the inverse hyperbolic tangent function has to be smaller than 1 (2nd boundary condition). This, in turn, implies that $v_0$ cannot be greater than $c_7$. If $v_0 = c_7$, then the argument of the inverse hyperbolic tangent function is exactly 1. This further implies that, if $v_0\sqrt{\frac{c_4}{c_1}} \leq 1$, then $\sqrt{\frac{c_1}{c_4}} \geq v_0$ and $v_{term} \geq v_0$. Consequently, if $c_1 = 0$, then $v_{term} = 0$, which implies that $v_0$ has to be zero as well, in order to keep $c_5$ real.

The condition of $c_1 \geq 0$ and its associated slope angles of $\theta \geq \tan^{-1}\mu$ are irrelevant, as even angles of $\theta > \tan^{-1}\mu$ can still be outside the gravity-powered domain. This means that at $c_1 = 0$ gravity can no longer accelerate the skier, as the forces accounting for non-conservative energy (drag and friction) decelerate the skier and therefore outweigh the effect of gravity. As such, there must exist a critical slope angle at which decelerating forces are in equilibrium with gravity, resulting in zero acceleration on an inclined slope. The critical slope angle, $\theta_{crit}$, can be derived from Equation (6), by setting the acceleration $a$ to zero. Solving for $\theta$ yields

$$\theta_{crit} = \sin^{-1}\left(\frac{\frac{c_4}{g}v^2 + \sqrt{-\frac{{c_4}^2\mu^2}{g^2}v^4 + \mu^2 + \mu^4}}{\mu^2 + 1}\right) \tag{20}$$

At $\theta_{crit}$, $v_{term} \equiv v_0$, which is evident as there is no acceleration at the boundary of the gravity-powered domain, which fulfills the basic condition of $v_{term} \geq v_0$ (argument of the inverse hyperbolic tangent function $\leq 1$). As $\theta_{crit} > \tan^{-1}\mu$ (unless $Al$ or $\mu$ are excessively and unrealistically high), $c_1 > 0$.

For the glide model, the following constants were pre-defined: initial velocities, $v_{0L}$ and $v_{0T}$, of leading and trailing skiers, respectively; initial displacements $x_{0L}$ and $x_{0T}$ (where $x_{0T} = 0$, and $x_{0L} = D_0$, i.e., the initial distance between the two skiers); body masses $m_L$ and $m_T$; $\theta$, $\mu$, $\rho$ (depending on altitude and air temperature of the slope) and $g$. The velocities, $v_L$ and $v_T$, and displacements, $x_L$ and $x_T$, were calculated numerically for each time step. $Ad$ and $Al$ (of leading and trailing skiers), defined as per fit functions of $D$ (**Figure 1**), were updated after each time step. $D$ is determined from $x_L$–$x_T$, and the ground made up by the trailing skier, $\Delta x$, equals $D_0$-$D$. $\Delta x$ was determined for $D_0$ ranging from 2 to 20 m, for glide distances from 5 to 200 m. Subsequently, the pre-defined constants were varied to understand different glide scenarios.

# RESULTS

**Figure 2** shows the basic principle of slipstreaming: the smaller $D$ and the longer the glide distance, the more ground can be made

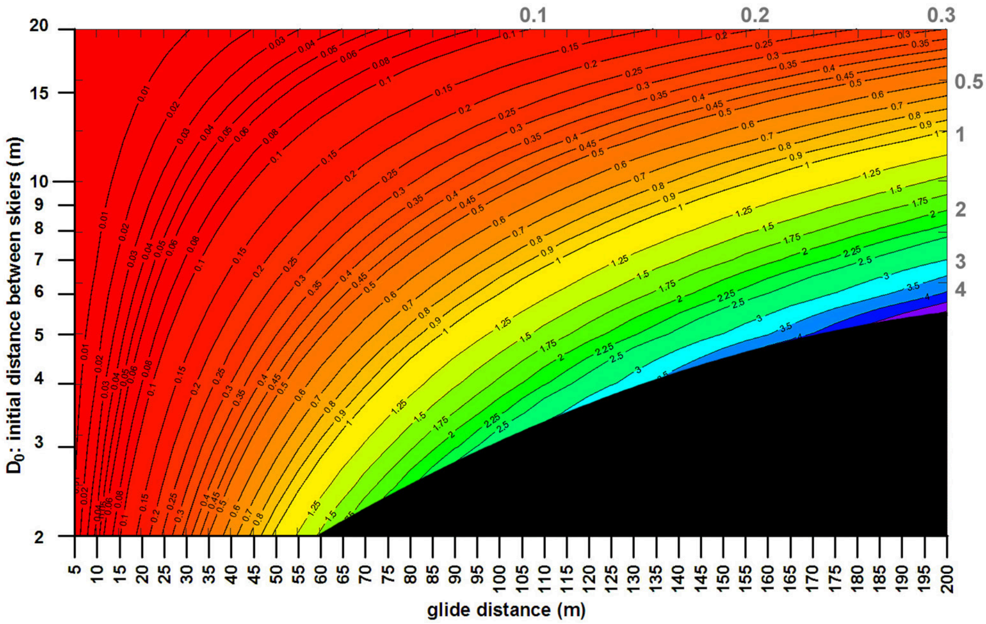


**FIGURE 2 |** Initial distance ($D_0$) between the two skiers against the glide distance; the contour lines (and the gray values at the top and right side of the plot) correspond to the ground made up (in meters) across the glide distance. The black triangle at the bottom right corner corresponds to unfeasible ground made up, i.e., the minimum distance between the skiers at the end of the glide distance is confined to 0.5 m. In this contour plot, the conditions for both skiers were as follows: mass (body plus gear) = 90 kg, kinetic friction coefficient between ski and snow = 0.05, initial speed at the beginning of the glide = 70 kph; slope angle = 20°; air density = 1.2 kg/m$^3$ (e.g., at 1,000 m altitude, −12.3°C, and humidity <60%). At these conditions, if the initial distance between the two skiers is 6 m at the beginning of the glide, then the ground made up after a 145 m glide is 2 m (contour), with a final distance of 4 m between the two skiers.

up ($\Delta x$) by closing the distance $D$. In **Figure 2**, the two skiers were at a high tuck position with identical conditions ($m = 90$ kg, $\mu = 0.05$, $v_0 = 70$kph; $\theta = 20°$; $\rho = 1.2$ kg/m$^3$). For example, at a glide distance of 100 m and $D_0 = 4$ m, $\Delta x$ equals 1.8 m. This value and its associated conditions will subsequently be referred to as the "*reference condition*," which further changing conditions will be compared to.

$\Delta x$ is only slightly dependent on speed. Compared to the reference condition and its $\Delta x$ of 1.8 m, $\Delta x = 1.88$ m at 90 kph and 1.69 m at 50 kph. If $D_0 = 10$ m, $\Delta x = 0.46$ m at 90 kph and 0.41 m at 50 kph. Slipstreaming is therefore slightly more effective at higher speeds.

If the velocities of the two skiers are different, making up ground depends on the speed differential. Compared to the reference condition, if the trailing skier is 10 kph faster (80 kph), only a 14.9 m glide distance over 0.65 s is required for catching up by 1.8 m (compared to 100 m or 4.28 s at an initial speed of 70 kph); it would take 15.3 m or 0.67 s without slipstreaming if the two skiers were racing side by side (not too close, though, as otherwise interference drag arises). If the trailing skier is only 1 kph slower (69 kph), then the distance between the two skiers will increase, in spite of slipstreaming, from 4 m to a maximum of 4.21 m after a glide of 31 m (or to 4.39 m without slipstreaming), and then return to 4 m after a 65.3 m glide (or further increase to 4.7 m without slipstreaming). Trailing at a speed of 65 kph, e.g., after having been overtaken by the leading skier, and entering the slipstream at 4 m distance, the distance between the two skiers will increase from 4 m to a maximum of 8.51 m after a glide of 181.7 m (and to 10.84 m without slipstreaming).

$\Delta x$ is dependent on the mass of the skiers, i.e., the lighter the pair of skiers, the more ground the trailing skier makes up over the same glide distance. Compared to the reference condition, $\Delta x = 2.34$ m if the mass of both skiers is 70 kg each, and 1.47 m at 110 kg.

If the masses of the two skiers are different, then Equation (16) explains why a trailing skier with less mass than the leading one is disadvantaged. Compared to the reference condition, if the trailing skier is 10 kg lighter (80 kg) or heavier (100 kg), $\Delta x$ is 0.61 m and 2.75 m, respectively. If the mass of the trailing skier is 75.7 kg at the same conditions, there is no gain from slipstreaming (<1.5 mm at 100 m). Beyond this critical mass, $\Delta x$ is negative and $D$ increases. This fact, however, should not discourage skiers from slipstreaming, as the loss in distance is worse without slipstreaming. At $D_0 = 10$ m, the critical mass of the trailing skier increases to 86.2 kg, only 3.8 kg less than the mass of the leading skier.

The friction coefficient $\mu$ has negligible influence on $\Delta x$. Compared to the reference condition, changing $\mu$ by $\pm$ 0.025 results in a change of $\Delta x$ by $\mp$ 0.015 m.

The air density $\rho$ changes with altitude, temperature and humidity, all of which are negatively correlated with $\rho$. $\rho$ and $\Delta x$ show the same behavior: less dense air results in smaller $\Delta x$; at small glide distances, the relative changes of $\rho$ and $\Delta x$ are similar;

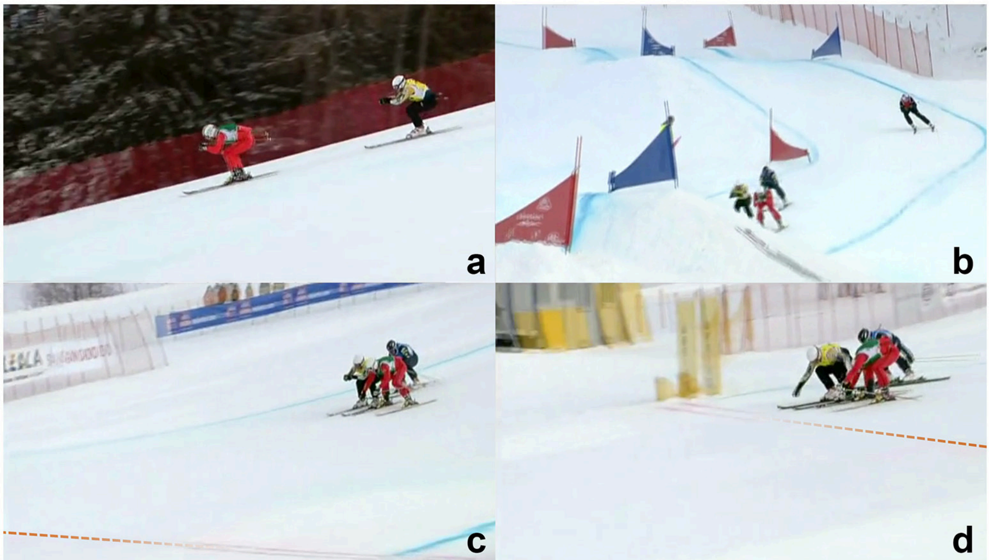


**FIGURE 3 |** Example of slipstreaming and overtaking in ski cross; FIS Freestyle World Cup event in Innichen—San Candido on December 19, 2010; **(a)** Scott Kneller (yellow) slipstreaming about 4 m behind Alex Fiva (red); **(b)** Kneller breaks out of the slipstream on the inner side of the last corner before the last jump; **(c)** shortly before the finish line (dashed), Kneller has already overtaken Fiva and maintains his aerodynamic position whereas Fiva has already opened up; **(d)** immediately before the finish line, Kneller is clearly leading; video screenshots from: https://vimeo.com/18009110, © Konrad Rotermund 2010, reproduced with kind permission.

at longer glide distances, the relative change of $\Delta x$ is slightly smaller than the one of $\rho$.

The slope angle $\theta$ is negatively correlated to $\Delta x$: the steeper $\theta$, the smaller is $\Delta x$. At the reference condition, $\Delta x = 1.8$ m; changing the slope angle to 10° and 30° results in $\Delta x$ of 1.93 and 1.73 m.

Changing the racing position from high to low tuck decreases the aerodynamic drag (roughly by 40% on average; Fuss, 2011). Reducing $Ad$ to 60% for both skiers at the reference condition shortens $\Delta x$ to approximately the same percentage (59% at short glide distances and 58% at 100 m). The lower the tuck position, the smaller is $\Delta x$. The influence of $Al$ on $\Delta x$ is negligible. When increasing $Al$ by 20%, $\Delta x$ decreases by <1% (at the reference condition).

Once the distance between the leading and trailing skiers has closed to an amount that requires the trailing skier to overtake the leading one, then the following questions arise:

- how does the suddenly increasing drag force, when breaking out of the slipstream, affect the trailing skier;
- is overtaking still possible under these circumstances; and, if yes,
- how long does it take to overtake the leading skier?

In principle, the tailing skier is always faster than the leading one, if the distance between the two skiers has decreased. The suddenly increasing drag force merely affects the acceleration of the trailing skier, whereas his/her velocity still increases due to gravity. The trailing skier should slipstream as long as practically possible and as long as he/she can overtake safely without endangering the leading skier.

For example, considering the reference condition, the trailing skier wants to break out of the slipstream at $D = 1.5$ m. This would happen after a glide distance of 116.6 m and a glide time of 4.88 s. The trailing skier then experiences the drag and lift he/she would without slipstreaming and will overtake the leading skier after a further glide of 35 m and 1.24 s. At that moment, the overtaking skier is 1.1 m/s faster (28.73 m/s).

Decreasing the slope angle (to 10°), or increasing the initial speed (to 90 kph), or increasing the skiers' mass (to 100 kg), does not substantially change the glide distance (112.6–122.8 m), nor the glide time (4.1–5.5 s), the further glide distance after leaving the slipstream (33–36.7 m), the further glide time (1.1–1.5 s) or the speed differential (0.89–1.24 m/s).

If the drag area of the reference condition is reduced to 60%, then the glide distance and time required for $D = 1.5$ m changes to 150.1 m and 5.83 s, and the glide distance and time required for overtaking changes to 44 m and 1.36 s. The speed differential at the time of overtaking is 1 m/s (at a total speed of 33.1 m/s). Therefore, slipstreaming enables faster overtaking.

## DISCUSSION

The explanation for the principles outlined in the Results section is found in Equation (5), rewritten as the ratio of:

$$\frac{(F_I)_{trailing}}{(F_I)_{leading}} = \frac{\left(F_{Gx} - \mu F_{Gy}\right)_{trailing} - (F_D - \mu F_L)_{trailing}}{\left(F_{Gx} - \mu F_{Gy}\right)_{leading} - (F_D - \mu F_L)_{leading}} \quad (21)$$

separated in gravitational and aerodynamic contribution on the right side.

The higher this ratio, the larger the acceleration of the trailing skier compared to the leading one, and the quicker the trailing skier can catch up. There is always a difference in $Al$ and $Ad$, i.e., in $F_L$ and $F_D$. Note that $\mu F_L << F_D$ and that $F_D$ is subtracted. Thus, if less drag is subtracted, the numerator increases and the ratio is greater than unity. Decreasing the mass of both skiers reduces the influence of the gravitational force such that the ratio, now dominated by the drag force, increases. Decreasing the slope angle reduces $F_{Gx}$, which in turn outweighs the increase of $F_{Gy}$ (as multiplied by $\mu$) so that the effect is the same as decreasing the mass. Opening up the tuck position subtracts more aerodynamic contribution from the same gravitational one (on either side of the division sign), which increases the ratio.

Slipstreaming has two decisive advantages: the slipstreaming athlete

- can catch up quicker with the leading one, or at least reduce speed loss caused by aerodynamic drag; and
- is able to save muscle energy.

The latter effect becomes apparent when comparing the advantage of slipstreaming to a reduction of aerodynamic drag by changing the body position without slipstreaming.

At the reference condition, making ground up of 1.8 m (100 m glide distance, 4.28 s glide time) has the same effect as reducing $Ad$ and $Al$ to 83.14% (4.3 s, 100 m) at a negligible 0.16% longer glide time. This can only be done by adopting a deeper tucked position, which consumes more muscle energy and also prevents the athlete from reacting quicker.

Putting this into an energy perspective, in terms of energy lost to drag and energy produced by the quadriceps muscle for maintaining the tucked position, results in the following data:

Slipstreaming: the energy of the trailing skier lost to drag (integral of drag force with gliding distance) amounts to 10.52 kJ; the increase in kinetic energy (initial speed: 19.4 m/s, final speed 26.9 m/s) equals 15.60 kJ.

Without slipstreaming, and instead reducing $Ad$ and $Al$ to 83.14%: the energy lost to drag is 11.61 kJ (i.e., 10.35% more energy is lost compared to the slipstreaming case); the increase in kinetic energy equals 14.57 kJ (i.e., the energy gain is 6.63% less than during slipstreaming).

In terms of comparing the muscle energies required for maintaining the two different body positions (higher tuck with slipstreaming and lower without), the relationship between energy expenditure of (isometric) contraction and muscle force produced must be known. According to Ortega et al. (2015), the isometric cost (unit: J) is a linear function of the force-time integral of the muscle. Based on a high tuck position (the aerodynamic data of which are shown in **Figures 1A–C**) and a lower tuck position (with an $Ad$ of 83.14% of the high tuck position), the summation COM (center of mass) of all body segments above the knee was calculated (based on the body segment data of Drillis and Contini, 1966; for a body height of 1.8 m and body+gear mass of 90 kg). The moments of $F_R$ and $F_F$ about the knee joint (minus the moments produced by the gravitational force of shanks, feet, boots and skis) resulted in 32.5 Nm and 62.4 Nm, respectively. This means that the knee moment in the lower tucked position was 1.92 times higher than in the high tucked one (slipstreaming condition), i.e., 92.20% higher. This relative relationship of the two knee moments does not mean that muscle force is also roughly 2 times higher, considering that that reducing the drag area requires a higher knee flexion angle (increase from 65 to 88°), which in turn decreases the (internal) moment arm of the patellar ligament as well as the mechanical advantage of the patellofemoral joint. Both factors would increase the muscle force (quadriceps); the muscle force is therefore expected to be greater than just 2 times the one at the higher tucked position. Neglecting the 0.16% longer glide time (for calculating the force-time integral), the isometric cost, and therefore the energy expenditure, of the quadriceps is estimated to be at least 2 times higher without slipstreaming compared to the slipstreaming condition.

These energy comparisons lead to recommendations for racing strategies in ski cross:

(1) General recommendations not necessarily confined to slipstreaming:

Tradeoff between aerodynamics and muscle energy expenditure:

From an aerodynamic point of view, the lowest tuck is the best choice. However, apart from the inability to react quickly to changing conditions, the muscle energy expenditure is higher, specifically for the quadriceps muscle.

In general, the lower the tucked position, the smaller is the drag area, so that less energy is lost to drag. Nevertheless, athletes cannot react that quickly to changing terrain features out of a deep tuck, and the risk of crashing is greater. This is why athletes prefer a higher tuck taking into account more energy lost to drag.

(2) Specific recommendations for slipstreaming:

Slipstreaming does have an advantage. Therefore, slipstreaming is recommended whenever feasible, as slipstreaming (a) increases the speed of the trailing skier relative to the leading one, or, at least, (b), minimizes the speed loss relative to the leading one.

In addition to this basic recommendation, there are situations when slipstreaming is more beneficial than in others:

The best results of quickly making up ground between the two skiers (i.e., increasing $\Delta x$) are achieved when the glide distances are long and the distance $D$ between the skiers is short. Glide distances do not have to be necessarily straight and do not end at a corner. Long glide distances invite the skier to maintain a low tuck as long as possible, which in turn decreases $\Delta x$. Therefore, slipstreaming at shorter glides and at higher tuck position also becomes advantageous as high tuck increases $\Delta x$. At larger $D$, $\Delta x$ can become very ineffective, which is not of concern as it is anyway difficult to remain in the slipstream at larger $D$. The apparent disadvantage of the trailing skier's mass being smaller than the one of the leading skier is actually an advantage, as slipstreaming still reduces the effect of the difference mass makes without slipstreaming. When slipstreaming, it is essential to have at least the same degree of tuck as the leading skier. If the body height of the trailing skier is greater than the one of the leading skier, then a tucked position lower than the one of the leading skier is advantageous for being perfectly in the slipstream. If the leading skier lowers his/her tucked position, the trailing skier has to follow in order to make most out of the slipstreaming principles. There is no direct advantage of slipstreaming at higher velocity differential, i.e., if the speed of trailing skier is substantially higher than the one of the leading skier. Although a trailing skier's speed smaller than the one of the leading skier seems disadvantageous, slipstreaming is still advantageous as it reduces the speed loss.

When the distance *D* between the two skiers closes to a safe minimum before colliding, overtaking is the logical consequence. The suddenly increasing drag force when breaking out of the slipstream does not slow down the trailing skier. The trailing skier is still faster than the leading one, and the increased drag force merely reduces the acceleration of the trailing skier slightly. The trailing skier is still accelerating due to gravity. Overtaking is of advantage immediately before, and on the inner side of, a corner.

A classical example of slipstreaming over a long distance is given by the FIS Freestyle World Cup event in Innichen—San Candido on December 19, 2010 (**Figure 3**), which Scott Kneller (AUS) won 6 weeks after wind tunnel testing. Kneller slipstreamed behind Alex Fiva (SUI) for most of the race (**Figure 3a**) and broke out of the slipstream (**Figure 3b**) on the inner side of the last corner before the last jump (https://vimeo.com/18009110). He overtook the leading Alex Fiva (SUI) on the last slope before the finish line (**Figure 3c**), only to win by approximately 20 cm. Kneller maintained an advantageous aerodynamic position almost until the finish line, whereas Fiva opened up his arms and thereby experienced a higher drag force (**Figure 3d**).

The glide model presented in this research can be used in the future for testing of slope track design. There is some data on tracks available on the internet (e.g., https://wiki.fis-ski.com/index.php/Ski_Cross_Courses), however they are only related to major sections of the track in terms of length and slope angle. If more details were available, including precise dimensions of terrain features, the speed of one or even more skiers can be modeled and critical sections can be identified.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

## ACKNOWLEDGMENTS

The authors would like to thank the two reviewers for their valuable comments and suggestions to improve the quality of the paper.

## REFERENCES

Barry, N., Burton, D., Sheridan, J., Thompson, M., and Brown, N. A. T. (2015). Aerodynamic drag interactions between cyclists in a team pursuit. *Sports Eng.* 18, 93–103. doi: 10.1007/s12283-015-0172-8

Barry, N., Sheridan, J., Burton, D., and Brown, N. A. T. (2014). The effect of spatial position on the aerodynamic interactions between cyclists. *Proc. Eng.* 72, 774–779. doi: 10.1016/j.proeng.2014.06.131

Broker, J. (1991). *Model of Skiing Aerodynamics for the United States Olympic Committee*. Colorado Springs, CO: United States Olympic Committee.

Drillis, R., and Contini, R. (1966). *Body Segment Parameters. Office of Vocational Rehabilitation*. Department Health, Education & Welfare. BP174-945, Tech.Rep (1166-03), School of Engineering and Science, New York University, New York, NY.

FIS (Fédération Internationale de Ski; International Ski Federation) (2017). *The International Freestyle Skiing Competition Rules (ICR)*. Oberhofen: International Ski Federation FIS, 100. Available online at: http://www.fis-ski.com/mm/Document/documentlibrary/FreestyleSkiing/08/62/43/FS_FIS_FreestyleICR2017_English.pdf).

Fuss, F. K. (2011). *Wind Tunnel Tests on Slipstreaming in Skiing; Report for the Winter Olympic Institute of Australia*. Melbourne, VIC: RMIT University.

Hoerner, S. F. (1965). *Fluid-Dynamic Drag*. Bakersfield, CA: Hoerner Fluid Dynamics.

Kirby, R. (2009). Development of a real-time performance measurement and feedback system for alpine skiers. *Sports Technol.* 2, 43–52. doi: 10.1002/jst.85

Luethi, S. M., and Denoth, J. (1987). The influence of aerodynamic and anthropometric factors on speed in skiing. *Intl. J. Sport Biomech.* 3, 345–352.

Nørstrud, H. (2008a). "Cross Country skiing," in *Sports Aerodynamics*, ed H. Nørstrud (Vienna: Springer), 107–130.

Nørstrud, H. (2008b). "Alpine downhill and speed skiing," in *Sports Aerodynamics*, ed H. Nørstrud (Vienna: Springer), 131–138.

Ortega, J. O., Lindstedt, S. L., Nelson, F. E., Jubrias, S. A., Kushmerick, M. J., and Conley, K. E. (2015). Muscle force, work and cost: a novel technique to revisit the Fenn effect. *J. Exper. Biol.* 218, 2075–2082. doi: 10.1242/jeb.114512

Pitcher, A. B. (2009). Optimal strategies for a two-runner model of middle-distance running. *SIAM J. Appl. Math.* 70, 1032–1046. doi: 10.1137/090749384

Rundell, K. W. (1996). Effects of drafting during short-track speed skating. *Med. Sci. Sports Exerc.* 28, 765–771.

**Conflict of Interest Statement:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

# Advantages of publishing in Frontiers

**OPEN ACCESS**
Articles are free to read for greatest visibility and readership

**FAST PUBLICATION**
Around 90 days from submission to decision

**HIGH QUALITY PEER-REVIEW**
Rigorous, collaborative, and constructive peer-review

**TRANSPARENT PEER-REVIEW**
Editors and reviewers acknowledged by name on published articles

**Frontiers**
Avenue du Tribunal-Fédéral 34
1005 Lausanne | Switzerland

**Visit us:** www.frontiersin.org
**Contact us:** info@frontiersin.org | +41 21 510 17 00

**REPRODUCIBILITY OF RESEARCH**
Support open data and methods to enhance research reproducibility

**DIGITAL PUBLISHING**
Articles designed for optimal readership across devices

**FOLLOW US**
@frontiersin

**IMPACT METRICS**
Advanced article metrics track visibility across digital media

**EXTENSIVE PROMOTION**
Marketing and promotion of impactful research

**LOOP RESEARCH NETWORK**
Our network increases your article's readership