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Health and performance assessment in winter sports - volume II

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Performance and Micro-Pacing Strategies in a Freestyle Cross-Country Skiing Distance Race

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This study examined the micro-pacing strategies during a distance freestyle cross-country (XC) skiing competition. Nine female and 10 male highly trained XC skiers wore a GNSS device during a FIS-sanctioned race. The course was ∼4900 m; women completed two-laps; men completed three-laps. The course was divided into uphill (S1, S3, S5, S7), downhill (S2, S4, S6, S8), and flat (S9) sections for analyses. Statistical parametric mapping was used to determine the course positions (clusters) where total race time or section time was significantly associated with instantaneous skiing speed. Total race time was associated with instantaneous skiing speed during a cluster in S1 on lap 2 for both sexes ($t \geq 5.899$, $p \leq 0.008$). The two longest uphill sections (S1; S5) and the flat section (S9) contained clusters where section times were related to instantaneous skiing speed for both sexes ($p < 0.05$). The fastest woman gained 6.9 s on the slowest woman during a cluster in S1 on lap 1 and 7.3 s during a cluster in S9 on lap 1. The fastest man gained 51.7 s on the slowest man over all clusters in S5 over the 3 laps combined. Compared to skiers with longer total race times, skiers with shorter race times skied with faster instantaneous speeds in some clusters of the uphill sections, as well as on the flat section of the course. This study also identified different relative micro-pacing strategies for women and men during freestyle distance XC skiing races. Finally, statistical parametric mapping analyses can help to identify individual strengths and weaknesses for guiding training programs and optimise competition pacing strategies.

Keywords: GNSS, GPS, skate skiing, statistical parametric mapping, tactics

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INTRODUCTION

International Ski Federation (FIS) cross-country (XC) skiing competitions are typically categorised into two main formats for individual events: sprint skiing (1.0–1.8 km) and distance skiing (≥ 10 and ≥ 15 km for women and men, respectively), and use either the freestyle or classical technique (The International Ski Federation, 2020). In addition to various competition distances and techniques, a further distinguishing characteristic of XC skiing events is the undulating terrain. The topography varies throughout the courses and contains approximately equal distances of uphill, downhill and flat sections (The International Ski Federation, 2020). Each of these factors influence a skier's distribution of effort throughout skiing races (i.e., the skier's pacing strategy) (Stöggl et al., 2018).

Researchers have previously focused on lap-to-lap pacing strategies adopted by XC skiers via changes in lap times over the duration of a race (Stöggl et al., 2018). More recently, it has been observed that skiers apply specific micro-pacing strategies within laps, which might be related to variations in the course topography (Andersson et al., 2010; Sandbakk et al., 2011, 2016; Ihalainen et al., 2020). For example, uphill sections have been identified as particularly critical to successful performance (Andersson et al., 2010; Sandbakk et al., 2011, 2016). In these sections, XC skiers typically exercise at intensities above their maximal aerobic power in order to maintain speed (Karlsson et al., 2018; Gløersen et al., 2020). Further, Ihalainen et al. (2020) observed that instantaneous skiing speed during distinct course sections, measured by a global navigation satellite system (GNSS) device, was related to overall sprint skiing performance in female skiers. Specifically, this study (Ihalainen et al., 2020) used a novel statistical technique termed statistical parametric mapping (SPM), which has recently been promoted as a useful tool for statistically analysing smooth continuous biomechanical data (Pataky, 2010, 2012). The use of GNSS and SPM can enable the comparison of skiing speeds between athletes at standardised course locations. The results from Ihalainen et al. (2020) identified that the skiing speeds during transitions between uphill and flat sections, and from flat or uphill to downhill sections, were strongly related to shorter race times (i.e., better performance).

It has been suggested that pacing strategies in XC skiing might vary depending on sex (Losnegard et al., 2016; Andersson et al., 2019; Ardigò et al., 2020), skiing technique (Stöggl et al., 2018; Ardigò et al., 2020) and competition distance (Losnegard et al., 2016). For instance, men tend to ski with a greater relative power output during uphill sections compared to women (Andersson et al., 2019). Additionally, men tend to ski faster particularly during transition periods between flat and uphill sections compared to women (Ardigò et al., 2020). Further, Losnegard et al. (2016) observed that both women and men adopted positive lap-to-lap pacing strategies during skating and classical technique competitions (i.e., faster initial laps compared to later laps). However, the fastest male skiers were able to maintain their lap speeds to a greater extent than their slower counterparts, whereas female skiers exhibited similar reductions in speed despite different overall performance levels. In addition, greater reductions in skiing speed were observed from the first to the last lap of a distance race with the classical technique compared to the skating technique (Losnegard et al., 2016). Finally, previous studies have highlighted that the reductions in skiing speed between laps appear to be greater in sprint compared to distance skiing (Stöggl et al., 2018). All taken together, it appears that sex, skiing technique and competition distance might influence pacing strategies in XC skiing.

Previous investigations of pacing strategies in XC skiing have focused mainly on sprint skiing (Andersson et al., 2010, 2016; Sandbakk et al., 2010, 2011), while less attention has been given to distance races (Stöggl et al., 2020). Stöggl et al. (2020) identified that elite-level skiers are capable of maintaining a more even pacing strategy during a long-distance skiing race, whereas amateur skiers tend to adopt a more positive pacing strategy. However, this study analysed only mean skiing speed through different sections of a course, rather than identifying how instantaneous speeds relate to section or total race times (Stöggl et al., 2020). To date, no study has applied SPM analyses to continuous GNSS data to understand within-lap micro-pacing strategies during distance skiing. Accordingly, it remains unclear how within-lap micro-pacing strategies relate to race performance during distance competitions for both women and men using the freestyle technique. Therefore, the aim of the present study was to apply SPM analyses to continuous GNSS data to analyse the within-lap micro-pacing strategies during a women's and men's distance freestyle XC skiing competition. This information could guide coaches and skiers in identifying how best to optimise pacing strategies and improve performance during these events.

MATERIALS AND METHODS

Participants

Nine female (age: 24 ± 3 years; distance FIS points: 73 ± 13) and ten male (age: 22 ± 1 years; distance FIS points: 68 ± 22) tier 3 athletes (McKay et al., 2022) competing in FIS-sanctioned freestyle distance XC skiing races agreed to participate in this study. All skiers provided written informed consent prior to participation and subsequently completed all requirements of the study. Ethical approval was granted by the ethical review board of Umeå University, Sweden (registration number: #2018-441-32M). All research was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Design

Skiers wore a commercial GNSS sensor (Catapult OptimEye S5, Catapult Sports, Melbourne Australia; dimensions: 96 × 52 × 13 mm; mass: 67 g) throughout the duration of the individual time-trial XC skiing races. The GNSS sensor was positioned on the centre of the skier's upper back at approximately the level of the superior angle of the scapulae using the harness provided by the manufacturer. The GNSS sensor recorded the skier's position at a sample frequency of 10 Hz throughout the duration of the race.

Prior to commencement of the race, skiers completed their usual warm-up and preparation routines. All preparation of the skis was conducted by professional ski technicians. The competition course was ∼4,900 m in distance, with a maximum climb of 63 and 165 m of total climbing. The women competed over two laps (total distance: 9,743 m) and the men competed over three laps (total distance: 14,678 m). As shown in **Figure 1**, the course was divided into discrete uphill (S1, S3, S5, S7), downhill (S2, S4, S6, S8), and flat sections (S9) for subsequent analysis. Due to different positions of the start, split and finish lines, the lap and section lengths varied slightly. For example, S1 on the second and third laps were slightly shorter (by ∼100 m) compared to the first lap. In addition, on the final lap for both the women and men, S9 was not included in the analyses since the finish line was close to the bottom of the final downhill section (S8).

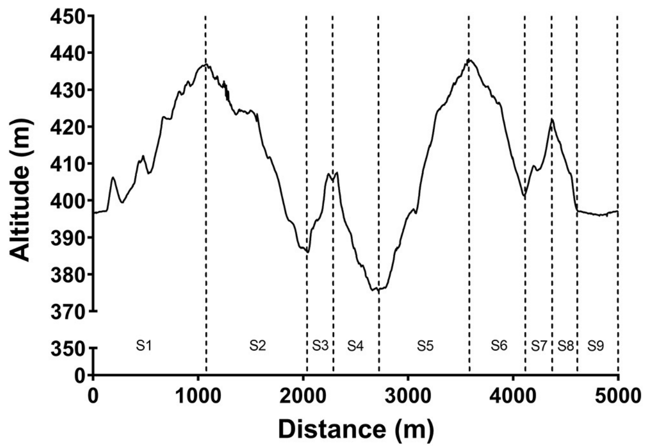

FIGURE 1 | A schematic of the course profile including specific uphill (S1, S3, S5, S7), downhill (S2, S4, S6, S8), and flat (S9) sections.

TABLE 1 | Mean ± standard deviation section times and Pearson correlation coefficients (r) between section times and total race time, with the associated 95% confidence interval (CI), for the women ($n = 9$).

	Lap 1		Lap 2	
	Time (s)	**r (95% CI)**	**Time (s)**	**r (95% CI)**
S1	226 ± 10	0.690* (0.047 to 0.928)	231 ± 11	0.945* (0.755 to 0.989)
S2	102 ± 2	0.747* (0.164 to 0.943)	106 ± 3	0.939* (0.732 to 0.987)
S3	67 ± 3	0.903* (0.596 to 0.980)	54 ± 3	0.666 (0.003 to 0.922)
S4	36 ± 1	0.288 (−0.465 to 0.799)	51 ± 2	0.879* (0.515 to 0.974)
S5	243 ± 11	0.954* (0.790 to 0.990)	250 ± 11	0.919* (0.655 to 0.983)
S6	55 ± 1	0.666 (0.003 to 0.922)	53 ± 1	0.699* (0.065 to 0.931)
S7	61 ± 3	0.887* (0.542 to 0.976)	57 ± 3	0.824* (0.354 to 0.962)
S8	24 ± 1	0.569 (−0.152 to 0.895)	46 ± 2	0.764* (0.203 to 0.925)
S9	62 ± 3	0.847* (0.419 to 0.967)	-	-

*$p < 0.05$.

Data Analysis

In order to apply a coordinate mapping procedure to the GNSS race data, a mapping trajectory was measured before the competition start using a differential GNSS (dGNSS) device (Leica Zeno GG04+, Leica Geosystems, Switzerland). The dGNSS device had a 1 cm ± 1 ppm horizontal and 2 cm ± 1 ppm vertical positional accuracy in the real-time kinematics mode that was used. Subsequently, positioning data from the race GNSS device was corrected using a reference trajectory according to methods previously described (Gløersen et al., 2018a; Ihalainen et al., 2020). Briefly, the positioning coordinates of the reference trajectory were filtered using a second order low-pass Butterworth filter set at 0.3 Hz. The filtered coordinates were subsequently resampled to every 1-m interval along the course using cubic spline interpolation. The GNSS positioning coordinates were then filtered using the same Butterworth filter. Filtered GNSS coordinates were subsequently mapped onto the reference trajectory, where the Euclidean distance between the measured position and the reference trajectory was minimised. The corrected GNSS data was then linearly interpolated to every 1-m interval to permit comparison of skiing speed at identical course locations. Section times and instantaneous speed for each skier was calculated from the GNSS data, which was downloaded from the device internal storage and analysed using the manufacturer provided software (Catapult OpenField; Catapult Sports, Melbourne Australia). The typical error of the GNSS system has been reported to be; Easting: 0.31 ± 0.06 m; Northing: 0.40 ± 0.12 m; Vertical: 0.58 ± 0.15 m (Gløersen et al., 2018b).

Statistical Analyses

Two-tailed Pearson's correlation coefficients were computed with IBM SPSS statistics 26 (IBM Co., Armonk, New York, USA) to examine the relationships between section times (within each separate lap) and total race time. The instantaneous speed curves (1-dimensional; 1D data) from all course sections that were significantly related to total race time were analysed using a SPM procedure using open-source SPM 1D software (Pataky, 2012) in MATLAB R2018a (The MathWorks, Inc., Natick, Massachusetts, USA). For each section of interest (based on Pearson's correlations), SPM 1D one-tailed linear regression models were applied to investigate the relationships between instantaneous speed and either section time or total race time. This resulted in SPM{t} curves with a critical threshold set at $\alpha = 0.05$. The SPM{t} curve represents the alpha value of the relationship between instantaneous speed and either section or total race time at every 1-m integer. Where the SPM{t} values exceeded the critical threshold, instantaneous speed was considered to be significantly related to the section or total race time. The course locations where the SPM{t} curve exceeded the critical threshold (i.e., the course locations where instantaneous speed and section time or total race time were significantly related) were computed. These sections are termed "SPM clusters." For each SPM cluster, the position within the section (start to end), the distance, duration, mean speed and the time difference between the fastest and the slowest skier was computed. Data are presented as mean ± standard deviation.

RESULTS

Women

Total race time was 28 min 44 ± 58 s. Section times and their associated correlations with total race time are presented in **Table 1**. There were significant positive linear relationships between section time and total race time for all sections ($p \leq 0.040$), except for the three latter downhill sections (S4, S6, and S8) on lap 1 and the second uphill section (S3) on lap 2.

The SPM regressions revealed that total race time was associated with instantaneous speed during parts of S1 on lap 2 ($t = 7.950$; $p = 0.004$; **Figure 2**). Specifically, shorter total race times were related to higher speeds over a 109-m cluster (at 523–632 m) within S1 on lap 2 ($p < 0.001$). During this cluster, mean skiing speed was 3.8 ± 0.2 m·s^{-1} and the fastest skier gained

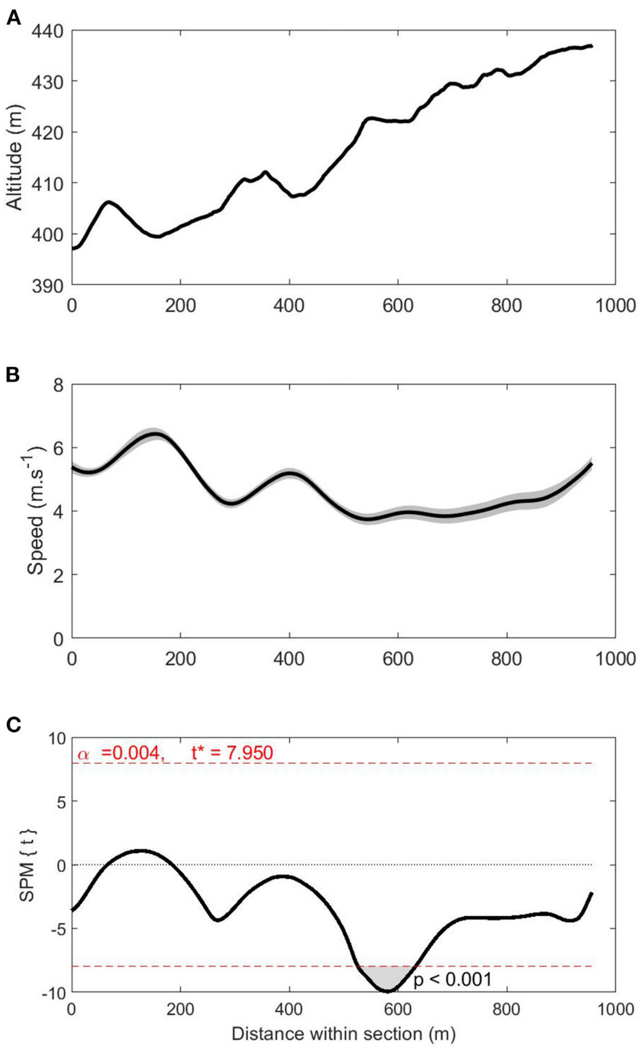

FIGURE 2 | Altitude (panel **A**), speed (panel **B**), and statistical parametric mapping (SPM{t}) curves (panel **C**) for the women in S1 on lap 2 (i.e., the course section where race time was significantly related to instantaneous skiing speed). The shaded area on the speed curve represents the 95% confidence interval. The shaded area on the SPM{t} curve shows the course location where a significant relationship exists between race time and instantaneous speed (at 523–632 m). *$p < 0.05$.

3.9 s on the slowest skier. No other significant associations were identified between total race time and instantaneous speed on specific course sections.

Table 2 displays the SPM clusters within each section where section time was significantly related to total race time. For each of these clusters the mean ± standard deviation time, speed and time gain (i.e., the time difference between the fastest and slowest skier) is also displayed. Despite significant relationships between section times and total race time, SPM regressions did not reveal any clusters where section time or total race time was related to instantaneous speed in S2, S3, S4, S6, or S8. The greatest time gains were observed in clusters on lap 1, in the latter part of the first uphill section (S1) and in the flat section (S9). Within these 2 clusters, the fastest skier gained 6.9 s and 7.3 s, respectively, on the slowest skier. Over all sections on the first and second laps, respectively, the fastest skier gained 17.7 s and 1.8 s on the slowest skier.

Men

Total race time was 38 min 37 ± 57 s. Section times and their associated correlations with total race time are presented in **Table 3**. There were significant positive linear relationships between section time and total race time for S5 (i.e., the longest of the four climbs) on all three laps ($p < 0.05$). In addition, there were significant positive linear relationships between section time and total race time for S1 (i.e., the second longest climb) on laps 2 and 3 ($p < 0.01$). There was also a significant positive linear relationship between section time and total race time for S9 (i.e., the flat section) on lap 2 ($r = 0.649$, $p = 0.042$).

The SPM regressions revealed that total race time was associated with instantaneous speed during parts of S1 on lap 2 ($t = 5.899$; $p = 0.008$; **Figure 3**). Specifically, shorter race times were related to higher speeds over a 184-m cluster (at 635–819 m) within S1 on lap 2 ($p < 0.01$). During this cluster, mean skiing speed was 4.6 ± 0.4 $m \cdot s^{-1}$ and the fastest skier gained 10.6 s on the slowest skier. No other significant associations were identified between total race time and instantaneous speed on specific course sections.

Table 4 displays the SPM clusters within each section where section time was significantly related to total race time. For each of these clusters the mean ± standard deviation time, speed and time gain (i.e., the time difference between the fastest and slowest

TABLE 2 | Characteristics of the SPM clusters where section time was significantly related to instantaneous speed for the women, with mean ± standard deviation time, velocity and time gain (i.e., the time difference between the fastest and slowest skier) for each cluster.

Lap	Section	Cluster start (m)	Cluster end (m)	Cluster distance (m)	Cluster duration (s)	Speed ($m \cdot s^{-1}$)	Time gain (s)
1	1	623	644	21	4.7 ± 0.2	4.3 ± 0.2	0.7
1	1	666	821	155	36.4 ± 2.0	4.3 ± 0.2	6.9
1	5	496	527	31	11.0 ± 0.6	2.8 ± 0.2	1.8
1	7	172	204	32	7.4 ± 0.3	4.4 ± 0.2	1.0
1	9	130	436	306	48.4 ± 2.2	6.4 ± 0.6	7.3
2	1	635	665	30	7.7 ± 0.5	3.9 ± 0.2	1.2
2	7	219	239	20	4.3 ± 0.2	4.6 ± 0.2	0.6

TABLE 3 | Mean ± standard deviation section times (s) and Pearson correlation coefficients (r) between section times and total race time, with the associated 95% confidence interval (CI), for the men ($n = 10$).

	Lap 1		Lap 2		Lap 3	
	Time (s)	**r (95% CI)**	**Time (s)**	**r (95% CI)**	**Time (s)**	**r (95% CI)**
S1	194 ± 5	0.334 (−0.374 to 0.796)	197 ± 9	0.888* (0.587 to 0.973)	204 ± 10	0.784* (0.305 to 0.946)
S2	94 ± 3	0.199 (−0.493 to 0.736)	98 ± 2	0.600 (−0.048 to 0.892)	99 ± 3	0.277 (−0.427 to 0.772)
S3	56 ± 2	0.438 (−0.264 to 0.837)	45 ± 2	0.629 (−0.001 to 0.902)	60 ± 3	0.481 (−0.214 to 0.852)
S4	33 ± 1	−0.098 (−0.685 to 0.567)	48 ± 1	0.597 (−0.052 to 0.892)	35 ± 1	0.280 (−0.424 to 0.772)
S5	210 ± 10	0.758* (0.245 to 0.939)	219 ± 10	0.854* (0.484 to 0.965)	218 ± 12	0.804* (0.352 to 0.962)
S6	51 ± 1	0.504 (−0.184 to 0.860)	51 ± 2	0.496 (−0.195 to 0.858)	50 ± 1	0.306 (−0.401 to 0.784)
S7	52 ± 2	0.381 (−0.327 to 0.815)	55 ± 3	0.485 (−0.208 to 0.854)	49 ± 2	0.079 (−0.579 to 0.675)
S8	23 ± 1	0.220 (−0.475 to 0.746)	24 ± 1	0.360 (−0.349 to 0.807)	43 ± 1	0.407 (−0.299 to 0.825)
S9	55 ± 2	0.524 (−0.158 to 0.867)	57 ± 2	0.649* (0.033 to 0.908)	-	-

*$p < 0.05$.

skier) is also displayed. The greatest time gains were observed in S5 on the second lap, where the fastest skier gained 20.4 s on the slowest skier. Over all clusters in S5 for all three laps combined, the fastest skier gained 51.7 s on the slowest skier. Over all sections on the first, second and third laps, respectively, the fastest skier gained 15.3 s, 35.5 s, and 26.6 s on the slowest skier.

DISCUSSION

This is the first study to our knowledge that has analysed micro-pacing strategies during a freestyle distance XC skiing race, using a method that allows comparison of skiing speed at standardised course locations. The main findings were that: (1) skiers with shorter total race or section times skied with higher instantaneous speeds in specific uphill and flat sections of the course; (2) compared to the less successful women, the more successful women skied faster in clusters within the three longer uphill sections (i.e., in S1 and S7 on both laps and in S5 on lap 1) and in the flat section (i.e., S9 on lap 1); 3) the more successful men skied faster in clusters within the two longest uphill sections (i.e., S1 on laps 2 and 3 and S5 on all 3 laps) and in the flat section (S9) on lap 2; 4) the fastest woman gained the most time in relation to the slowest woman in S1 and S9 on lap 1, while the fastest man gained the most time in relation to the slowest man in S5 on lap 2; 5) statistical parametric mapping is a valuable tool for analysing micro-pacing strategies and could be practically useful when providing pacing and performance feedback to athletes and coaches.

Previous research has identified the importance of uphill sections in determining overall performance in XC skiing (Andersson et al., 2010; Sandbakk et al., 2011, 2016). Specifically, Sundström et al. (2013) used computerised modelling to demonstrate that an optimal pacing strategy is characterised by increased propulsive power during uphill course sections. In addition, Ihalainen et al. (2020) observed that instantaneous skiing speeds in particular parts of uphill sections were related to section or total race times in a women's classic sprint XC skiing race. The present study support and extend these previous findings by describing the micro-pacing strategies during a freestyle distance race for both women and men. In particular, the two longest uphill sections (S1 and S5), as well as the flat course section (S9), contained clusters where section and/or total race times were related to instantaneous skiing speed for both sexes. For example, in the women's race the fastest skier gained 6.9 s on the slowest skier during a cluster in S1 on the first lap, and gained 7.3 s during a cluster in the flat section (S9). In the men's race, the fastest skier gained 51.7 s on the slowest skier over all clusters in S5 for all three laps combined. This finding further contributes to the notion that uphill sections are particularly critical to success in XC skiing and provides valuable information to coaches and skiers to inform pacing strategies and training programs.

The largest time gain between the fastest and slowest female skier in a single course section (i.e., 7.3 s) was observed in the flat section (S9) at the end of the first lap. By contrast, the largest time gain observed between the fastest and slowest male skier (i.e., 20.4 s) was in the longest uphill section (S5) on the second lap. These findings might reflect different micro-pacing strategies adopted between sexes, as well as different relative strengths in women and men. Sex differences in the fastest vs. slowest skier might be explained by variations in skiing speed during transitional periods between flat and uphill sections (Ardigò et al., 2020). Although the FIS points were similar between sexes in the present study, there was a greater variation in the male athletes, which might explain why larger time differences were observed in this cohort. Additionally, sex differences in the fastest vs. slowest skier might be explained by variations in relative power outputs (Andersson et al., 2019). Further, Losnegard et al. (2016) observed that the most successful male skiers were able to maintain a more even lap-to-lap pacing strategy in comparison to their slower counterparts during a distance XC skiing race. On the other hand, there was little difference in the lap-to-lap pacing strategy between the fastest and slowest female skiers (Losnegard et al., 2016). The present study supports these findings, whereby the largest time difference between the fastest and slowest skiers was observed on the first lap for the women, but on the second and third laps for the men. This suggests that lower-performing male skiers might benefit from adopting a more even lap-to-lap pacing strategy. Further studies could attempt to investigate the effects of altering pacing

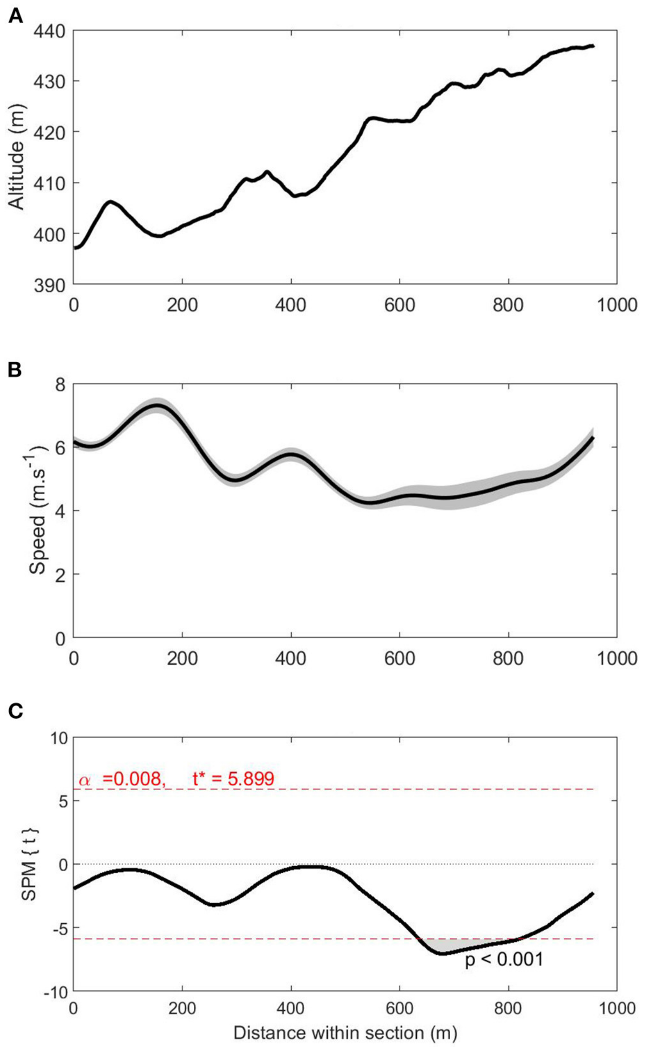

FIGURE 3 | Altitude (panel **A**), speed (panel **B**), and statistical parametric mapping (SPM{t}) curves (panel **C**) for the men in S1 on lap 2 (i.e., the course section where race time was significantly related to instantaneous skiing speed). The shaded area on the speed curve represents the 95% confidence interval. The shaded area on the SPM{t} curve shows the course location where a significant relationship exists between race time and instantaneous speed (at 635–819 m). $^{*}p < 0.05$.

strategies in the field, and/or implementing training strategies to improve pacing among competitive XC skiers.

The present study demonstrated that shorter total race times were not related to higher instantaneous skiing speeds during downhill sections for either the women or men. However, section time in S2 (one of the downhill sections) was related to total race time for the women. Previous research has reported that downhill section times were not related to shorter race times in XC sprint skiing races (Andersson et al., 2010; Sandbakk et al., 2011). However, these studies only observed pacing strategies for men participating in sprint competitions, but not for women. The results from the present study suggest that downhill skiing performance might be more important for success among women during freestyle distance competitions.

Previous research has mainly focused on lap-to-lap pacing strategies in XC skiing (Andersson et al., 2010; Sandbakk et al., 2011, 2016; Swarén and Eriksson, 2019). For example, lap times in XC ski races tend to become slower over the duration of a race (i.e., positive pacing) (Stöggl et al., 2018). Whilst this information is useful, it provides limited understanding of a skier's distribution of effort within each lap. The present study provides novel insights for XC skiers and coaches and demonstrates that SPM analyses can provide practical information to optimise pacing strategies. Using historical data, coaches and sports scientists could use SPM analyses to identify crucial components for success on various courses and race formats in order to guide pacing strategies prior to an event. In addition, individual skiers' strengths and weaknesses can be identified and used to guide training programs.

A limitation of the present study is the lack of accounting for skiers using drafting tactics. The methodological approach assumed that skiers adopted micro-pacing strategies independent of other competitors on the course. Although the race was performed as an individual time-trial, skiers were still able to overtake and be overtaken, which may have led to drafting tactics having positive aerodynamic and physiological effects (Bilodeau et al., 1994, 1995). Accordingly, it is possible that individual micro-pacing strategies were influenced by other skiers on the course. Second, waxing strategies of the skis can affect overall race performance. Because ski waxes have different effects at different skiing speeds, waxing strategies might influence section times along the course and hence the SPM analyses. Third, the data in the present study represent a freestyle XC skiing distance race from only one course location. The generalisability of these findings to other courses with different topographical profiles, race distances, techniques, and skiers remain to be confirmed. Nevertheless, the methodological approach in this study has utility for sports scientists and coaches to optimise pacing strategies and improve performance for any skier at any course location.

CONCLUSION

Specific uphill and flat course sections were identified where skiers with shorter total race times skied with faster instantaneous speeds compared to skiers with longer race times. More specifically, successful skiers had faster instantaneous speeds in some clusters of the uphill sections, as well as on the flat section of the course. In addition, this study identified that relative micro-pacing strategies differed between the women and men during their freestyle distance XC skiing races. Specifically, in the women's race the largest time gain between the fastest and slowest skier was observed in the flat section at the end of the first lap (S9; 7.3 s). By contrast, the largest time gain observed between the fastest and slowest male skier was in the longest uphill section on the second lap (S5; 20.4 s). Finally, SPM analyses can be used by coaches

TABLE 4 | Characteristics of the SPM clusters where section time was significantly related to instantaneous speed for the men, with mean ± standard deviation time, velocity, and time gain (i.e., the time difference between the fastest and slowest skier) for each cluster.

Lap	Section	Cluster Start (m)	Cluster End (m)	Cluster Distance (m)	Cluster duration (s)	Speed (m·s^{-1})	Time gain (s)
1	5	187	354	167	41.6 ± 2.0	4.0 ± 0.2	5.9
1	5	433	617	184	54.1 ± 3.4	3.4 ± 0.4	9.4
2	1	557	741	184	41.9 ± 3.2	3.9 ± 0.6	8.7
2	5	268	647	379	108.3 ± 6.7	3.6 ± 0.4	20.4
2	9	154	436	282	41.5 ± 2.2	6.8 ± 0.5	6.4
3	1	253	312	59	12.2 ± 0.5	4.9 ± 0.3	1.6
3	1	479	699	220	51.2 ± 3.1	4.3 ± 0.3	9.0
3	5	163	277	114	29.7 ± 1.7	3.8 ± 0.2	5.1
3	5	372	454	82	24.7 ± 1.7	3.4 ± 0.3	5.0
3	5	496	592	96	28.5 ± 2.1	3.4 ± 0.3	5.9

and athletes to identify individual athletes' strengths and weaknesses for guiding training programs and to optimise pacing strategies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the regional ethical review board of Umeå University, Sweden (#2018-441-32M). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CS performed the data analysis, statistical analyses, and wrote the manuscript. SC performed the SPM analysis, constructed SPM figures and provided editorial assistance in writing the manuscript. ØK provided editorial assistance in writing the manuscript. MS assisted with data analysis and provided editorial assistance in writing the manuscript. SI participated in the design of the study and collected the data. KM participated in the design of the manuscript, supervised the project and provided editorial assistance in writing the manuscript. All authors have read and approved the final version of the manuscript.

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The Effect of Rifle Carriage on the Physiological and Accelerometer Responses During Biathlon Skiing

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Purpose: Investigate the effect of biathlon rifle carriage on physiological and accelerometer-derived responses during biathlon skiing.

Methods: Twenty-eight biathletes (11F, 17M) completed two XC skiing time-trials (∼2,300 m), once with and once without the biathlon rifle, with concurrent measurements of HR, skiing speed and accelerations recorded from three triaxial accelerometers attached at the Upper-spine, Lower-spine and Pelvis. Exercise intensity was quantified from HR, skiing speed as well from accelerometry-derived PlayerLoad™ per minute (PL·min^{-1}) and average net force (AvF$_{Net}$). All metrics were analyzed during Uphill, Flat and Downhill sections of the course. Relationships between accelerometry-derived metrics and skiing speed were examined.

Results: Time-trials were faster for males compared with females (mean difference: 97 ± 73 s) and No-Rifle compared to With-Rifle (mean difference: 16 ± 9 s). HR was greatest during Downhill (183 ± 5 bpm), followed by Uphill (181 ± 5 bpm) and was lowest in the Flat sections (177 ± 6 bpm, $p<0.05$). For PL·min^{-1} and AvF$_{Net}$ there were 3-way Rifle x Gradient x Sensor-Position interactions. Typically, these metrics were greatest during Uphill and Flat sections and were lowest during Downhill sections. Rifle carriage had no impact on the AvF$_{Net}$ at the Lower-Spine or Pelvis. Significant positive linear relationships were identified between skiing speed and accelerometer-derived metrics during Uphill, Flat and Downhill skiing ($r = 0.12$–0.61, $p < 0.05$).

Conclusions: The accelerometry-derived approach used in this study provides the potential of a novel method of monitoring the external demands during skiing. In particular, AvF$_{Net}$ with sensors located close to the center of mass displayed greatest utility because it followed the expected response of external intensity where responses were greatest during uphill sections, followed by flats and lowest during downhills. In addition, there were significant positive relationships between AvF$_{Net}$ and skiing speed ranging from small to large. Accelerometry-derived measures could provide useful estimates of the external demands in XC skiing and biathlon.

Keywords: athlete, IMU, physiology, PlayerLoad™, undulating terrain

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INTRODUCTION

Biathlon is an Olympic winter sport which combines cross-country (XC) skiing using the skating technique with precision shooting. Performance in biathlon is determined by a mixture of skiing speed, shooting accuracy and shooting time (Laaksonen et al., 2018). It has been suggested that the skiing component of biathlon can explain 50–65% of the variation in overall performance, depending on the specific biathlon event (Luchsinger et al., 2018, 2019, 2020).

During the skiing component of biathlon competitions, athletes are required to carry a rifle (minimum mass: 3.5 kg) harnessed on their back. Despite this, it has been reported that even top-level biathletes complete surprisingly little (15–20%) of their endurance training actually carrying the rifle (Laaksonen et al., 2018). Regardless, several researchers have observed that the rifle carriage increases the physiological responses (i.e., energy cost, heart rate (HR) and blood lactate) whilst roller-skiing on a treadmill (Rundell and Szmedra, 1998; Stöggl et al., 2015; Jonsson Kårström et al., 2019). However, limited research has observed the impact of rifle carriage on physiological responses in actual on-snow conditions. It is useful for coaches and athletes to understand how rifle carriage impacts physiological response to XC skiing during biathlon competitions and training sessions.

It is common for coaches and athletes in biathlon (and XC skiing) to utilize HR as a means of prescribing and monitoring the internal responses to exercise (Tønnessen et al., 2014). The basis of HR as a measure of exercise intensity is rooted in the assumption of a linear relationship between HR and $\dot{V}O_2$ during steady-state sub-maximal intensity exercise (Hopkins, 1991), where research has shown nearly perfect correlation coefficients ($r = 0.99$) (Swain et al., 1998; Schrack et al., 2014). However, previous studies have demonstrated that skiers are exposed to supramaximal intensity efforts during the uphill sections of a XC skiing course (i.e., contribution from anaerobic energy sources) (Karlsson et al., 2018; Gløersen et al., 2020). Further, other studies have demonstrated that XC skiers employ pacing strategies during competitions which means that the metabolic intensity during biathlon and XC skiing is intermittent (Björklund et al., 2011; Andersson et al., 2016). Therefore, the utility of HR as a measure of exercise intensity in XC skiing and biathlon is questionable.

Wearable accelerometers offer a measurement system to quantify the external demands of sports in a manner which can overcome the limitations of HR. This is because accelerometers have a sufficient measurement resolution to reflect instantaneous changes in exercise intensity during intermittent activity (Boyd et al., 2011; Staunton et al., 2017). In addition, wearable accelerometers offer a measurement system which might be able to quantify the biomechanical intensity of activity in addition with the locomotor demands (Boyd et al., 2011; Vanrenterghem et al., 2017). Accordingly, accelerometry-derived metrics, such as PlayerLoad^{TM} (PL) and average net force (AvF_{Net}), have readily been used for athlete monitoring in team sports, such as basketball (Staunton et al., 2017, 2018a), soccer (Scott et al., 2013; Dalen et al., 2016), and Australian football (Cormack et al., 2013; Mooney et al., 2013).

One of the major contributors to accelerometry-derived measures of exercise are the vertical ground reaction forces experienced during foot strikes whilst running (Boyd et al., 2011). As a consequence, it is known that very strong relationships exist between running speed and both PL (Barrett et al., 2014) and AvF_{Net} (Staunton et al., 2017) during over ground running. However, accelerometry-derived metrics, such as PL and AvF_{Net}, have not been utilized to monitor the external demands during any form of on-snow skiing. Therefore, the relationships between accelerometer-derived metrics with locomotion speed during on-snow skiing remain unknown, despite the potential implications of these relationships on the utility of accelerometry for monitoring the external demands during skiing.

Therefore, the aims of this study were to investigate: (1) the impact of rifle carriage on the physiological responses to the XC skiing component of biathlon during on-snow conditions; and (2) the utility of accelerometry as a means to measure the external demand of the XC skiing component of biathlon, including investigating relationships with skiing speed.

METHODS

Participants

In accordance with the primary aim of this study, an a-priori power calculation was conducted in G*Power using a repeated measured ANOVA within factors (gradient: three levels) model. It was determined that 28 participants were needed to provide 80% power at an alpha value of 0.05 assuming a true effect size and correlation among repeated measures that was moderate ($f = 0.25$; $r = 0.5$) and a non-sphericity correction equal to 1. Accordingly, 28 biathletes (11 females: Age: 19 ± 2 years, Stature: 167 ± 7 cm, Body mass: 68 ± 10 kg; 17 males: Age: 19 ± 2 years; Stature: 181 ± 5 cm; Body mass: 74 ± 6 kg) who regularly compete in biathlon were recruited to participate in this study. The biathletes were developmental tier 2 athletes according to participant classification framework (McKay et al., 2022). All participants provided written informed consent and completed all requirements of the study. The regional ethical review board in Umeå, Sweden (registration number: 2016-506-31M) preapproved the research techniques and experimental protocol. All research was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Design

Participants completed two maximal effort XC skiing time-trials, once with and once without carrying the biathlon rifle in a randomized-counterbalanced order. During the time-trials, athletes wore the MyoMotion (Noraxon Inc., Scottsdale, AZ, USA) 3D motion analysis system which consisted of 12 inertial measurement units (IMU) attached to various points of the body. The MyoMotion system contains inertial sensors which provides information of bodily movements recording at 100 Hz (technical specifications: accelerometer: ± 16 g; gyroscrope: ± 2,000°·s^{-1}; magnetometer: ±1.9 gauss). The MyoMotion system has confirmed validity and reliability (Yoon, 2017; Yoon et al., 2019) for measuring three-dimensional angular movements.

Accelerations derived from three of the 12 IMUs were used for analysis in this study. Those were the three IMUs positioned along the spine and included the Pelvis, Lower-Spine and the Upper-Spine positions (**Figure 1**). These positions were chosen because they are commonly used attachment points for measuring exercise volume and intensity in sports (Barrett et al., 2014; Staunton et al., 2017). Additionally, skiing speed was calculated from the change in position per time (Forerunner 920; Garmin, Olathe, KS, USA), HR (Polar Electro OY, Kempele, Finland) was recorded throughout the time-trials and blood lactate (Bla) was recorded immediately prior to- and 2-min post time-trial.

Skiing Course

Prior to commencement of the time-trials, athletes completed a standardized 15-min warm-up which comprised of familiarization of the time-trial loop and dynamic bodily movements. The time-trials were performed at the Swedish National Biathlon Arena on a race circuit which is regularly included in the IBU world cup event. The circuit was ~2,300 m in distance with a total climb of 95 m. Participants competed at least 20-min of self-regulated active recovery between time-trial efforts, which previous research has demonstrated is sufficient for blood lactate clearance (Vesterinen et al., 2009; Menzies et al., 2010). The course was divided into discrete uphill (U1, U2, U3, U4, U5, U6, U7), downhill (D1, D2, D3, D4, D5, D6, D7), and flat sections (F1, F2, F3) for analyses by visual inspection of the altitude profile from the positioning system worn by athletes (**Figure 2**).

Data Analyses

Accelerometer data from the Pelvis, Lower-Spine and Upper-Spine IMUs were downloaded using the manufacturer software (MyoResearch v3.6.2; Noraxon Inc., Scottsdale, AZ, USA). MyoMotion acceleration data were continuously transformed from sensor to world coordinates by applying a sensor fusion algorithm from the onboard gyroscopes and magnetometers. Accordingly, 1 g was subtracted from the vertical axis in order to remove the gravitational component from the acceleration signal. Following this, a low-pass 4th order Butterworth filter with a cut-off frequency of 15 Hz was used to remove the noise component of the signal. This frequency was identified from visual inspection of the energy spectrum of the acceleration signal and is closely aligned with previous research which has used similar low-pass filter frequencies during sports (Wundersitz et al., 2015a,b).

Exercise intensity was quantified from the accelerometer signals for each section of the skiing course and in each sensor position in two ways. Firstly, PlayerLoad™ per minute ($PL \cdot min^{-1}$) was calculated as previously described (Boyd et al., 2011). Briefly, PL is calculated as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three axes (X, Y, and Z axis) and divided by 100. Subsequently, the accumulated PL for each section of the skiing course was divided by the time taken to calculate $PL \cdot min^{-1}$.

Secondly, accelerometry-derived average net force (AvF_{Net}) was calculated as previously described (Equation 1) (Staunton et al., 2017, 2018a,b, 2020). Briefly, the product of the filtered instantaneous resultant acceleration vector and participant's body mass was used to determine instantaneous net force (F_{Net}), which was then averaged over user selected periods. This metric has confirmed construct validity to measure exercise intensity in basketball (Staunton et al., 2017) and is strongly correlated with $\dot{V}O_2$ and running speed on flat surfaces (Staunton et al., 2017, 2018a). The rifle mass was not included in the AvF_{Net} calculation during the with-rifle trial in order to determine the impact of the rifle on the accelerometer response.

$$AvF_{Net} = BM \times \frac{\sum_{i=1}^{n} \left(\sqrt{a_{x_i}^2 + a_{y_i}^2 + a_{z_i}^2} \right)}{n} \quad (1)$$

Equation 1: Accelerometry-derived average net force.

AvF_{Net} = Average net force, BM = body mass, a_x = acceleration in the x direction, a_y = acceleration in the y direction, a_z = acceleration in the z direction, n = number of samples.

In addition, mean HR (% maximum activity) and skiing speed ($m \cdot s^{-1}$) were calculated for each section of the skiing track. Blood lactate (Bla) was recorded approximately 2-min prior to the beginning of each time-trial and approximately 2-min following completion of each time-trial using an automated analyzer (Biosen S-line; EKF diagnostics, Magdeburg, Germany).

For the purposes of comparing uphill, downhill and flat sections, all metrics from the uphill sections (U1, U2, U3, U4, U5, U6, U7) were averaged and considered as Uphill; all metrics from the downhill sections (D1, D2, D3, D4, D5, D6, D7) were averaged and considered as Downhill; and all flat sections (F1, F2, F3) were averaged and considered as Flat.

Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics (Version 27.0; IBM Corporation, NY) with level of significance set at $\alpha < 0.05$. Shapiro-Wilk tests confirmed that the assumption of normality was not violated and group data were expressed as mean ± standard deviation (SD). A two-way mixed-model analysis of variance (ANOVA) was used to determine the effect of Sex (Between Factors: Female; Male) and/or Rifle (Within Factors: With-Rifle; No-Rifle) on time-trial performance. Repeated measures two-way ANOVAs (within factors: Gradient; Rifle) were used to identify if Gradient (Uphill; Downhill; Flat) and/or Rifle (With-Rifle; No-Rifle) influenced the response of HR throughout the time-trial. Repeated measures two-way ANOVAs (within factors: Timing; Rifle) were used to identify if Timing (Baseline; Pre; Post) and/or Rifle (With-Rifle; No-Rifle) influenced the response of Bla to the time-trial. Repeated measures three-way ANOVAs (within factors: Gradient; Rifle; Sensor Position) were used to identify if Gradient (Uphill; Downhill; Flat); Rifle (With-Rifle; No-Rifle) and/or Sensor Position (Upper-Spine; Lower-Spine; Pelvis) influenced the response of accelerometry-derived metrics ($PL \cdot min^{-1}$; AvF_{Net}) throughout the time-trial. Significant interactions were followed up with simple main effect analyses with pairwise comparisons using Bonferroni correction. Furthermore, Pearson correlation

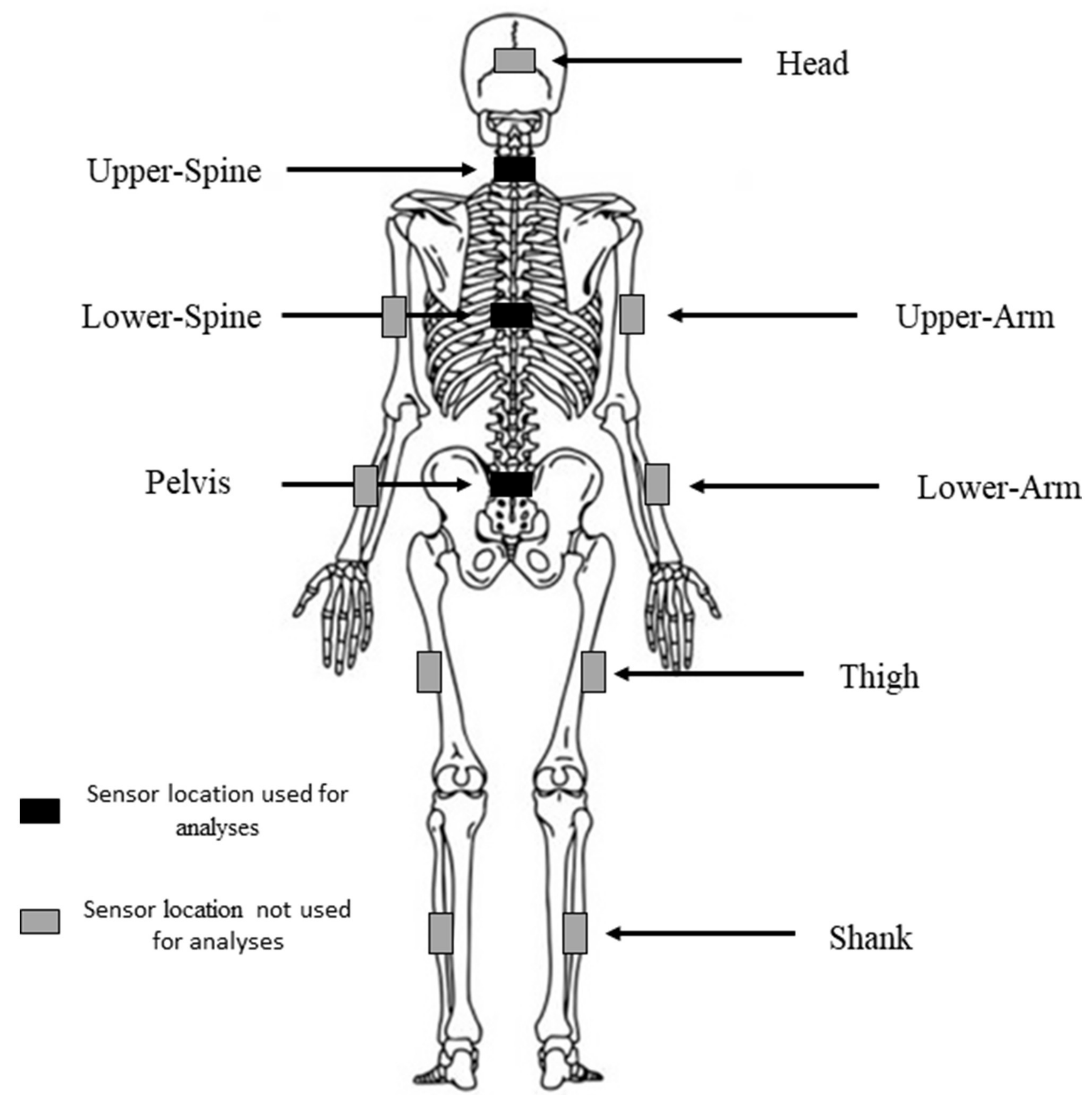

FIGURE 1 | Depiction of the IMU sensor locations during the XC skiing time-trials.

coefficients (r) were used to examine the strength of relationship between skiing speed and accelerometer-derived metrics during Uphill, Downhill and Flat skiing sections at all sensor locations. To compare the strength of relationship between skiing speed and accelerometer-derived metrics at all sensor locations, the Pearson correlation coefficient r values were z-transformed using Fisher's z-transformation (Fisher, 1915). This analysis identified that there was minimal differences in the strength of relationship between sensor locations. Accordingly, for simplicity, only the relationships obtained at the Pelvis sensor location are reported because this is considered as the criterion sensor location due to being closest to the center of mass (Halsey et al., 2011). Strength of relationships were evaluated according to methods previously stated (Hopkins, 2002). Very

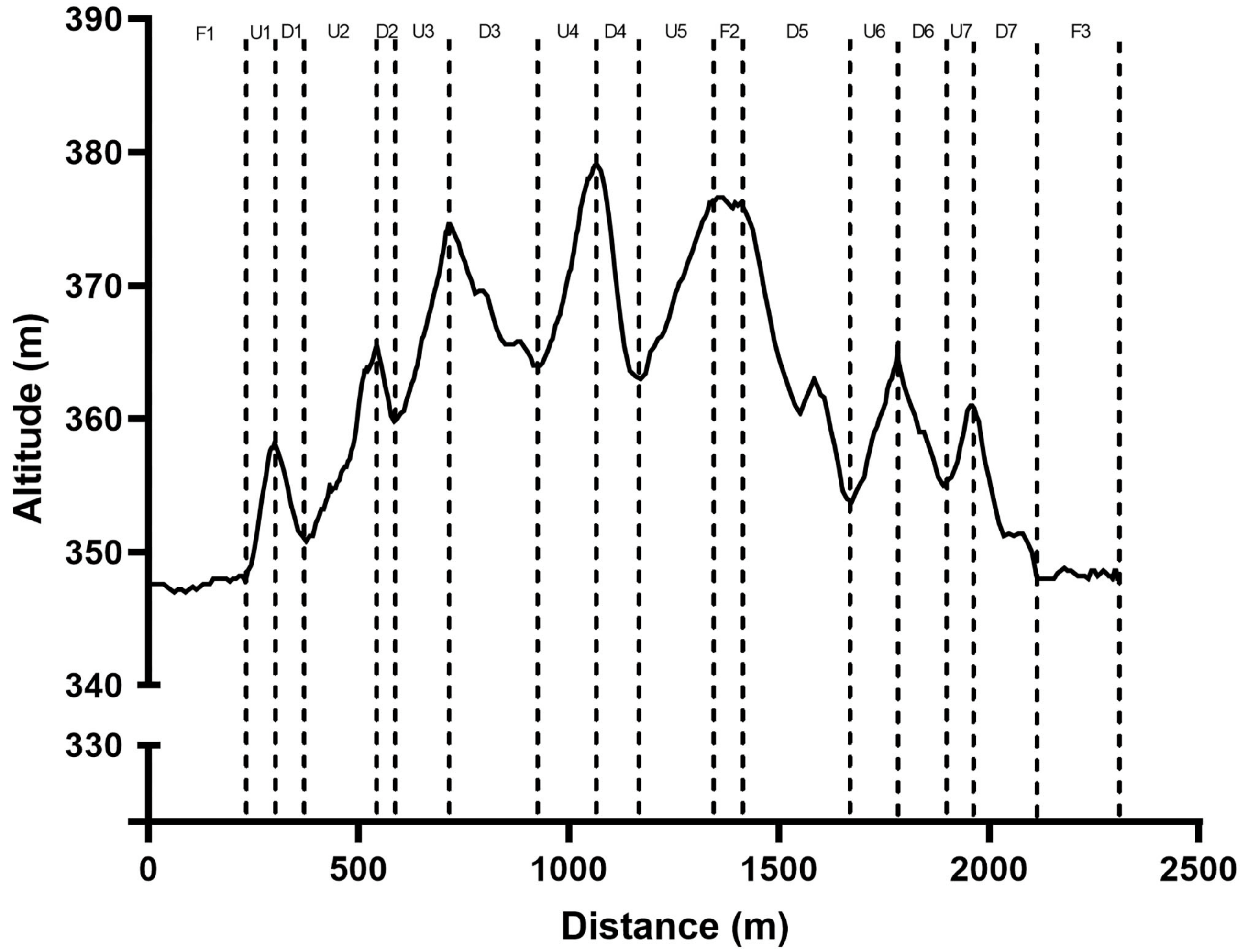

FIGURE 2 | Course profile including Uphill, Flat and Downhill sections. U, Uphill; F, Flat; D, Downhill.

small correlations were 0.0–0.1; small correlations were 0.1–0.3; moderate correlations were 0.3–0.5; large correlations were 0.5–0.7; very large correlations were 0.7–0.9 and nearly perfect correlations were 0.9–1.0.

RESULTS

Time-Trial

Section and total time for all time-trials are shown in **Table 1**. There was no Rifle x Sex interaction [$F_{(1,26)} = 2.593$, $p = 0.119$] for time-trial performance. However, there was a main effect for both Rifle [$F_{(1,26)} = 86.829$, $p < 0.001$] and Sex [$F_{(1,26)} = 49.113$, $p < 0.001$]. Time-trials were faster for males compared with females (mean difference: 97 ± 73 s) and No-Rifle compared to With-Rifle (mean difference: 16 ± 9 s).

Physiological Data

Physiological data (HR and Bla) are displayed in **Figure 3**. For HR, there was no Gradient x Rifle interaction [$F_{(2,54)} = 0.023$, $p = 0.914$] or main effect for Rifle [$F_{(1,26)} = 0.899$, $p = 0.352$]. However, there was a main effect for Gradient [$F_{(2,54)} = 225.442$, $p < 0.001$]. All pairwise comparisons between Gradient were different ($p < 0.001$). HR was greatest during Downhill sections (98 ± 1%), followed by Uphill (97 ± 1%) and was lowest in the Flat sections (94 ± 2%).

For Bla, there was no Rifle x Timing interaction [$F_{(1,28)} = 0.393$, $p = 0.521$]. Also, there was no main effect for Rifle [$F_{(1,28)} = 0.290$, $p = 0.595$], suggesting that rifle carriage has no impact on Bla and that the rest periods between time-trials was sufficient for recovery. As expected there was a timing effect [$F_{(1,28)} = 542.338$, $p < 0.001$], where Bla was elevated post time-trial (11.4 ± 2.8 $mmol{\cdot}L^{-1}$) compared to pre time-trial (2.2 ± 1.1 $mmol{\cdot}L^{-1}$).

PlayerLoad™

Figure 4 displays the mean $PL{\cdot}min^{-1}$ across all conditions. There was a 3-way Rifle x Gradient x Sensor Position interaction [$F_{(4,104)} = 10.641$, $p < 0.001$]. At the Upper-Spine there was a main effect for Gradient [$F_{(2,54)} = 85.590$, $p < 0.001$] where

TABLE 1 | Section and total time (s) for both sexes with and without rifle carriage.

Section	Female		Male	
	With-Rifle	No-Rifle	With-Rifle	No-Rifle
F1	36 ± 5	36 ± 5	29 ± 2	28 ± 2
UH1	27 ± 4	25 ± 5	18 ± 2	17 ± 3
DH1	13 ± 2	13 ± 2	11 ± 2	12 ± 1
UH2	56 ± 8	54 ± 10	40 ± 4	38 ± 5
DH2	8 ± 1	9 ± 1	8 ± 1	8 ± 1
UH3	45 ± 6	43 ± 6	33 ± 3	31 ± 3
DH3	24 ± 3	24 ± 3	21 ± 4	23 ± 4
UH4	67 ± 13	62 ± 12	47 ± 8	42 ± 7
DH4	15 ± 3	14 ± 1	14 ± 2	13 ± 2
UH5	47 ± 6	43 ± 5	34 ± 4	33 ± 4
F2	21 ± 3	19 ± 1	16 ± 2	16 ± 2
DH5	28 ± 2	27 ± 2	26 ± 2	26 ± 2
UH6	25 ± 5	24 ± 4	20 ± 2	19 ± 3
DH6	15 ± 1	14 ± 1	14 ± 1	14 ± 1
UH7	16 ± 3	15 ± 3	12 ± 1	11 ± 1
DH7	12 ± 1	12 ± 2	11 ± 4	12 ± 3
F3	34 ± 5	33 ± 7	31 ± 6	30 ± 7
TOTAL*#	488 ± 51	469 ± 49	388 ± 21	375 ± 25

*All values are mean ± SD; *indicates significant main effect for Sex (p < 0.05); #indicates main effect for Rifle (p < 0.05). UH, Uphill; F, Flat; DH, Downhill.*

all gradients were statistically different ($p < 0.001$). PL·min^{-1} was greatest during Flat sections (10.7 ± 3.3 arb.u), followed by Uphill (9.4 ± 2.6 arb.u) and was lowest for Downhill sections (6.7 ± 1.8 arb.u). At the Lower-Spine there was a Rifle x Gradient interaction [$F_{(2,52)} = 30.944$, $p < 0.001$]. PL·min^{-1} was greater With-Rifle compared to No-Rifle during all Gradients ($p < 0.001$ for all). With-Rifle, PL·min^{-1} was greater for Uphill and Flat sections compared to Downhill ($p < 0.001$ for both), but there was no difference between Uphill and Flat sections ($p = 0.556$). However, for No-Rifle, PL·min^{-1} was different between all Gradients ($p < 0.001$ for all), being greatest for Flat sections (12.9 ± 4.1 arb. u), followed by Uphill (11.7 ± 2.7 arb. u) and was lowest for Downhill (10.3 ± 2.1 arb. u). At the Pelvis there was a Rifle x Gradient interaction [$F_{(2,52)} = 24.046$, $p < 0.001$]. PL·min^{-1} was greater With-Rifle compared to No-Rifle during all Gradients ($p < 0.001$ for all). With-Rifle, PL·min^{-1} was greater for Uphill and Flat sections compared to Downhill ($p < 0.001$ for both), but no difference between Uphill and Flat sections ($p = 1.000$). For No-Rifle, PL·min^{-1} was similar across all Gradients ($p = 1.000$ for all).

Average Net Force

Figure 5 displays the AvF_{Net} across all conditions. There was a 3-way Rifle x Gradient x Sensor Position interaction [$F_{(4,104)} = 2.921$, $p = 0.037$]. At the Upper-Spine there was a Rifle x Gradient interaction [$F_{(2,54)} = 8.494$ $p < 0.001$]. AvF_{Net} was greater for No-Rifle compared to With-Rifle during Uphill ($p < 0.001$), Downhill ($p = 0.003$) and Flat ($p < 0.001$) Gradients. With-Rifle, AvF_{Net} was greater for Uphill and Flat sections compared to Downhill ($p < 0.001$ for both). There was no difference between Uphill and Flat sections ($p = 0.632$). For No-Rifle, AvF_{Net} was greater for Uphill and Flat sections compared to Downhill ($p < 0.001$ for both). There was no difference between Uphill and Flat sections ($p = 1.000$). At the Lower-Spine there was a Gradient effect [$F_{(2,54)} = 203.904$, $p < 0.001$]. All pairwise comparisons for Gradient were different ($p < 0.001$ for all). AvF_{Net} was greatest during Uphill (352 ± 67 N), followed by the Flat sections (321 ± 65 N), and with Downhill sections the lowest (261 ± 56 N). At the Pelvis there was a Gradient effect [$F_{(2,54)} = 118.983$, $p < 0.001$]. All pairwise comparisons for Gradient were different ($p < 0.001$ for all). AvF_{Net} followed the expected response where the Uphill section was the greatest (389 ± 73 N), followed by the Flat sections (361 ± 77 N), with Downhill the lowest (291 ± 60 N).

Correlations

Figure 6 displays the correlations between PL·min^{-1} (for the pelvis sensor) and skiing speed for Uphill (**Figures 6A,B**), Flat (**Figures 6C,D**) and Downhill (**Figures 6E,F**) track sections for both No-Rifle and With-Rifle conditions. For Uphill sections, the correlations between skiing speed and PL·min^{-1} were small for With-Rifle [$r = 0.16$ (95%CI: 0.02–0.30), $p = 0.024$] and moderate for No-Rifle [$r = 0.34$ (95%CI: 0.21–0.46), $p < 0.001$; **Figures 6A,B**]. For Flat sections, the correlations between skiing speed and PL·min^{-1} were insignificant and small for With-Rifle [$r = 0.12$ (95%CI: −0.01 to 0.33), $p = 0.315$] and large for No-Rifle [$r = 0.61$ (95%CI: 0.45–0.72), $p < 0.001$; **Figures 6C,D**]. For Downhill sections, the correlations between skiing speed and PL·min^{-1} were small for With-Rifle [$r = 0.25$ (95%CI: 0.11–0.37), $p < 0.001$] and large for No-Rifle [$r = 0.59$ (95%CI: 0.48–0.67), $p < 0.001$; **Figures 6E,F**].

Figure 7 displays the correlations between AvF_{Net} (for the pelvis sensor) and skiing speed for Uphill (**Figures 7A,B**), Flat (**Figures 7C,D**) and Downhill (**Figures 7E,F**) track sections for both No-Rifle and With-Rifle conditions. For Uphill sections, the correlations between skiing speed and AvF_{Net} were small for With-Rifle [$r = 0.28$ (95%CI: 0.14–0.40), $p < 0.001$] and moderate for No-Rifle [$r = 0.41$ (95%CI: 0.28–0.52), $p < 0.001$; **Figures 7A,B**]. For Flat sections, the correlations between skiing speed and AvF_{Net} were moderate for With-Rifle [$r = 0.32$ (95%CI: 0.11–0.50), $p = 0.003$] and moderate for No-Rifle [$r = 0.52$ (95%CI: 0.34–0.66), $p < 0.001$; **Figures 7C,D**]. For Downhill sections, the correlations between skiing speed and AvF_{Net} were moderate for With-Rifle [$r = 0.35$ (95%CI: 0.22–0.47), $p < 0.001$] and moderate for No-Rifle [$r = 0.36$ (95%CI: 0.23–0.47), $p < 0.001$; **Figures 7E,F**].

DISCUSSION

This is the first study to quantify accelerometry-derived measures of external demand, as well as physiological responses to a XC skiing time-trial, performed in ecologically valid on-snow conditions, with and without the biathlon rifle. The main findings of this study were: (1) the biathlon rifle had little impact on the mean physiological responses, as neither HR nor

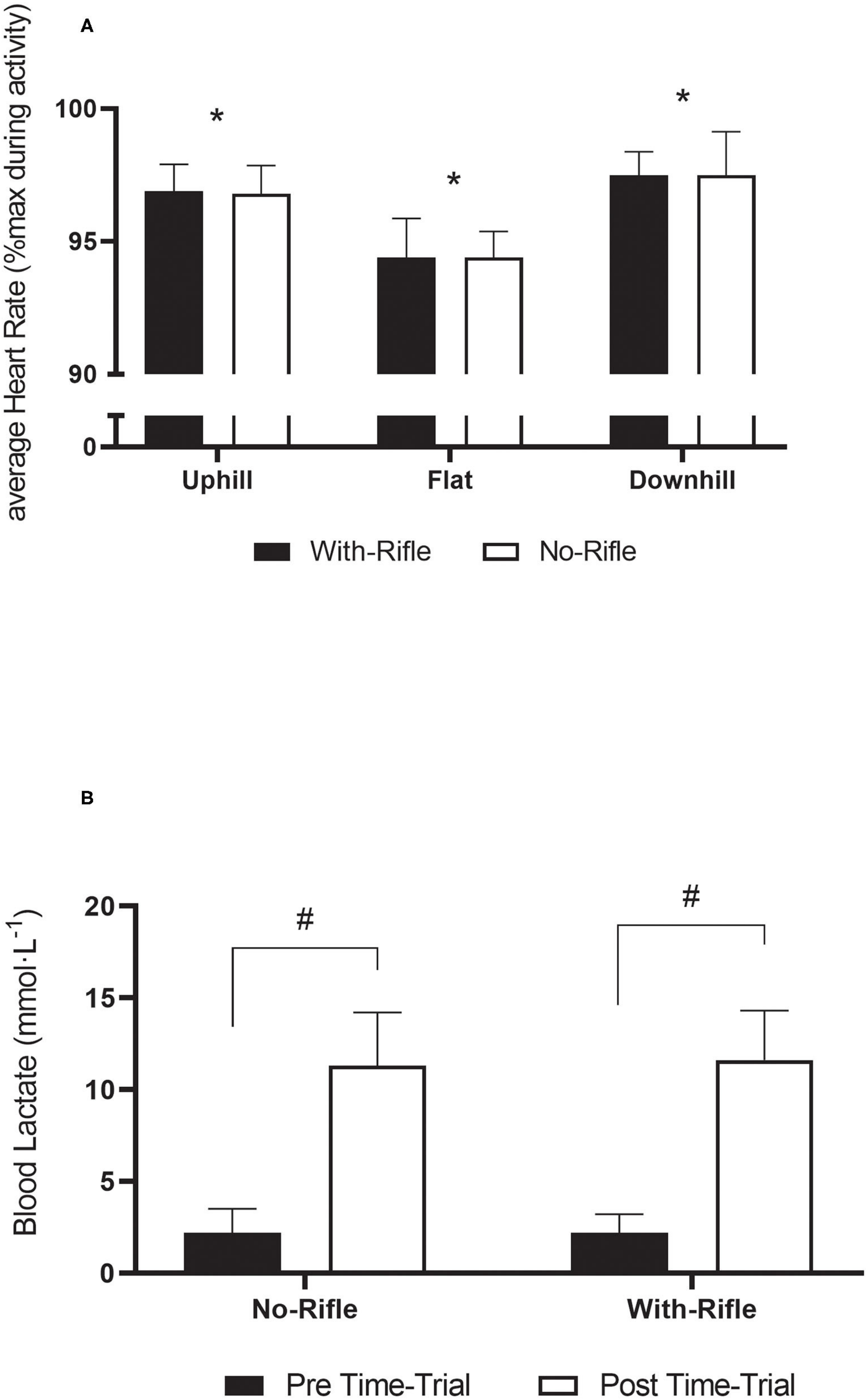

FIGURE 3 | Heart rate **(A)** and blood lactate **(B)** responses to the time-trials. Mean ± standard deviation. *Indicates different to With-Rifle ($p < 0.001$); #indicates different to pre time-trial ($p < 0.001$).

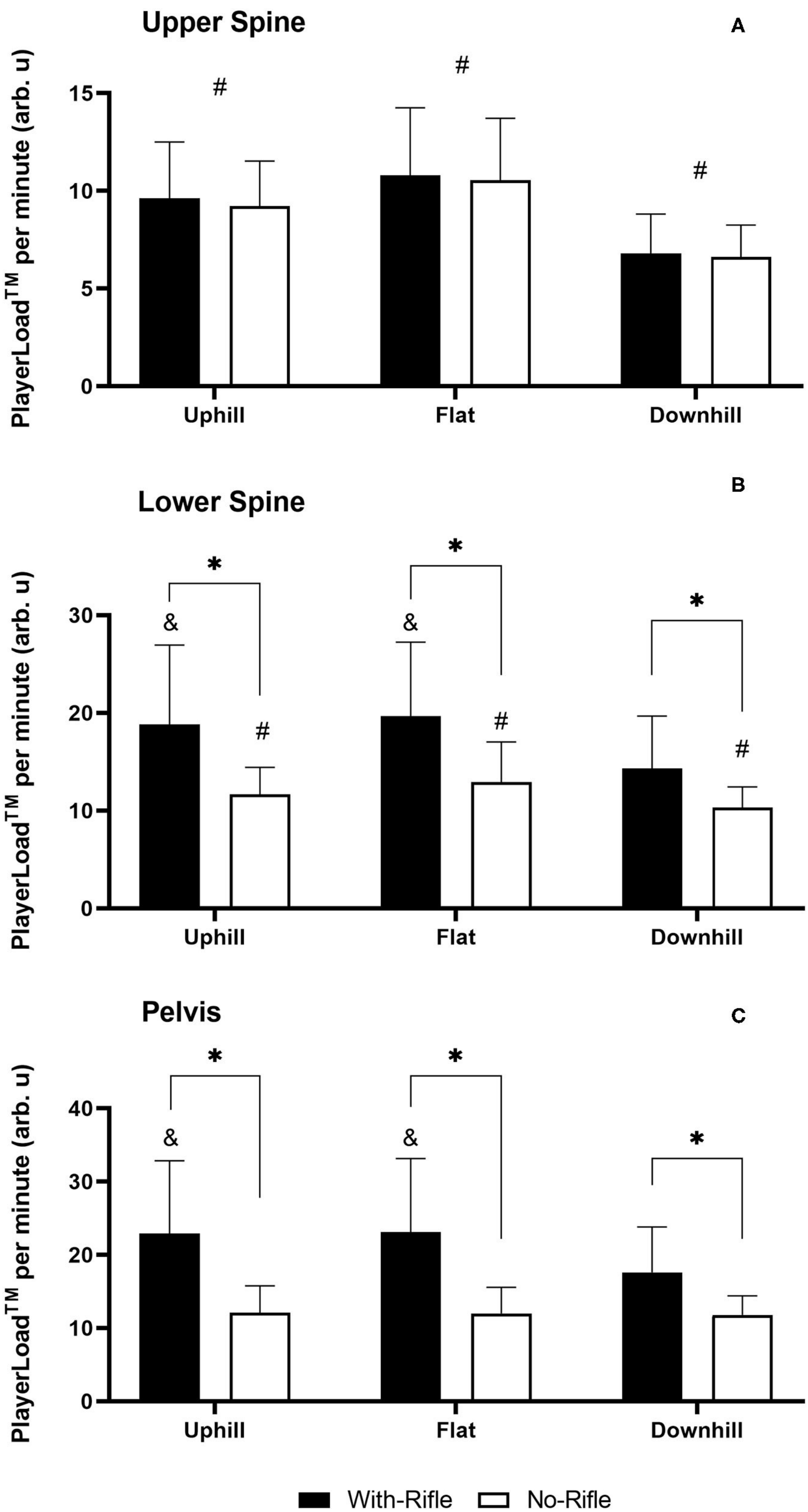

FIGURE 4 | PlayerLoad™ per minute With-Rifle and No-Rifle for all gradients for each sensor position. **(A)** Upper Spine; **(B)** Lower Spine; and **(C)** Pelvis. Mean ± standard deviation. *different to With-Rifle within condition ($p < 0.001$); #different to all other gradients ($p < 0.001$); &different to Downhill within condition ($p < 0.001$).

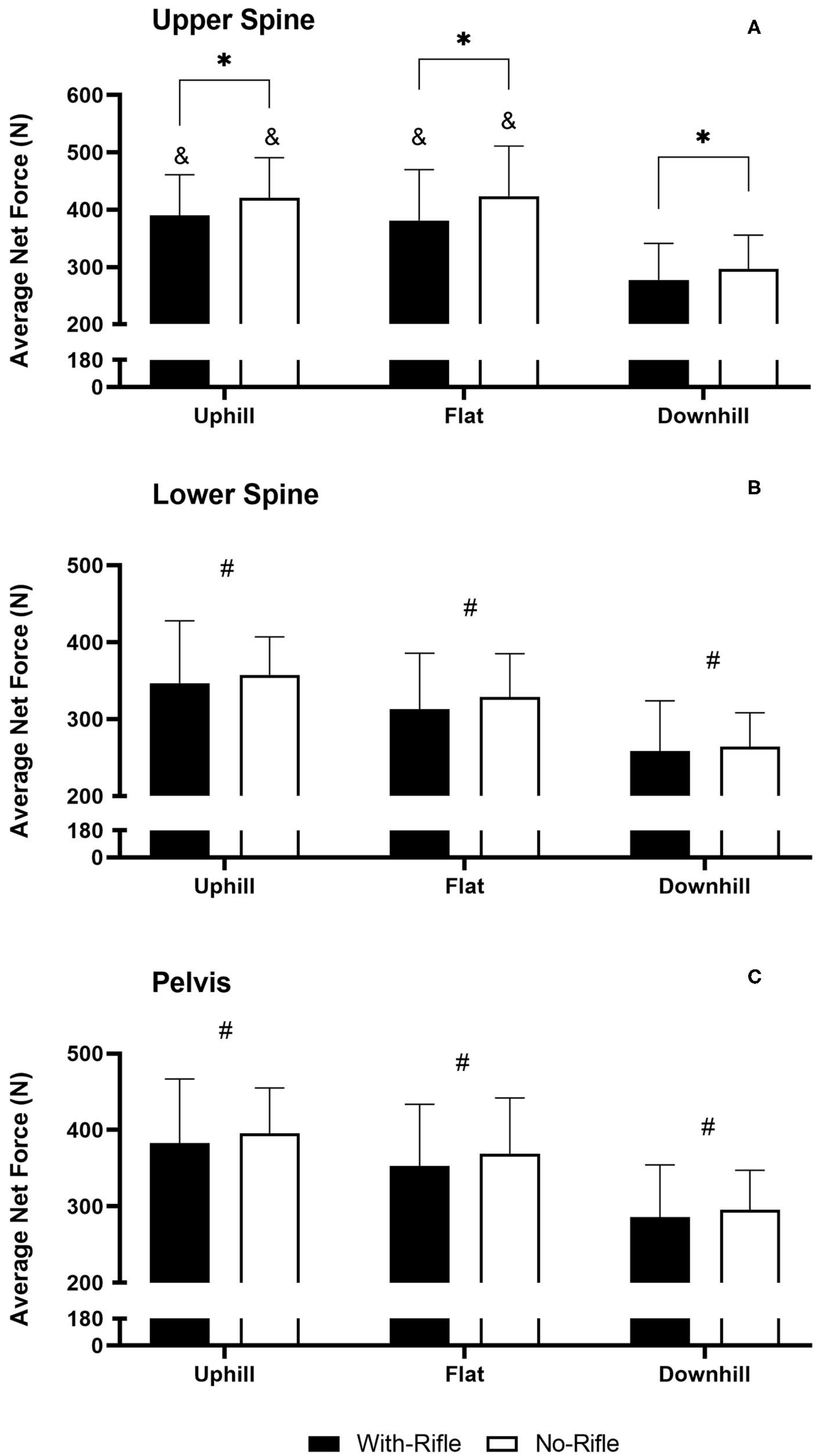

FIGURE 5 | Average Net Force With-Rifle and No-Rifle for all gradients for each sensor position. **(A)** Upper Spine; **(B)** Lower Spine; and **(C)** Pelvis. Mean ± standard deviation. *different to With-Rifle within condition ($p \leq 0.003$); #different to all other gradients ($p < 0.001$); &different to Downhill within condition ($p < 0.001$).

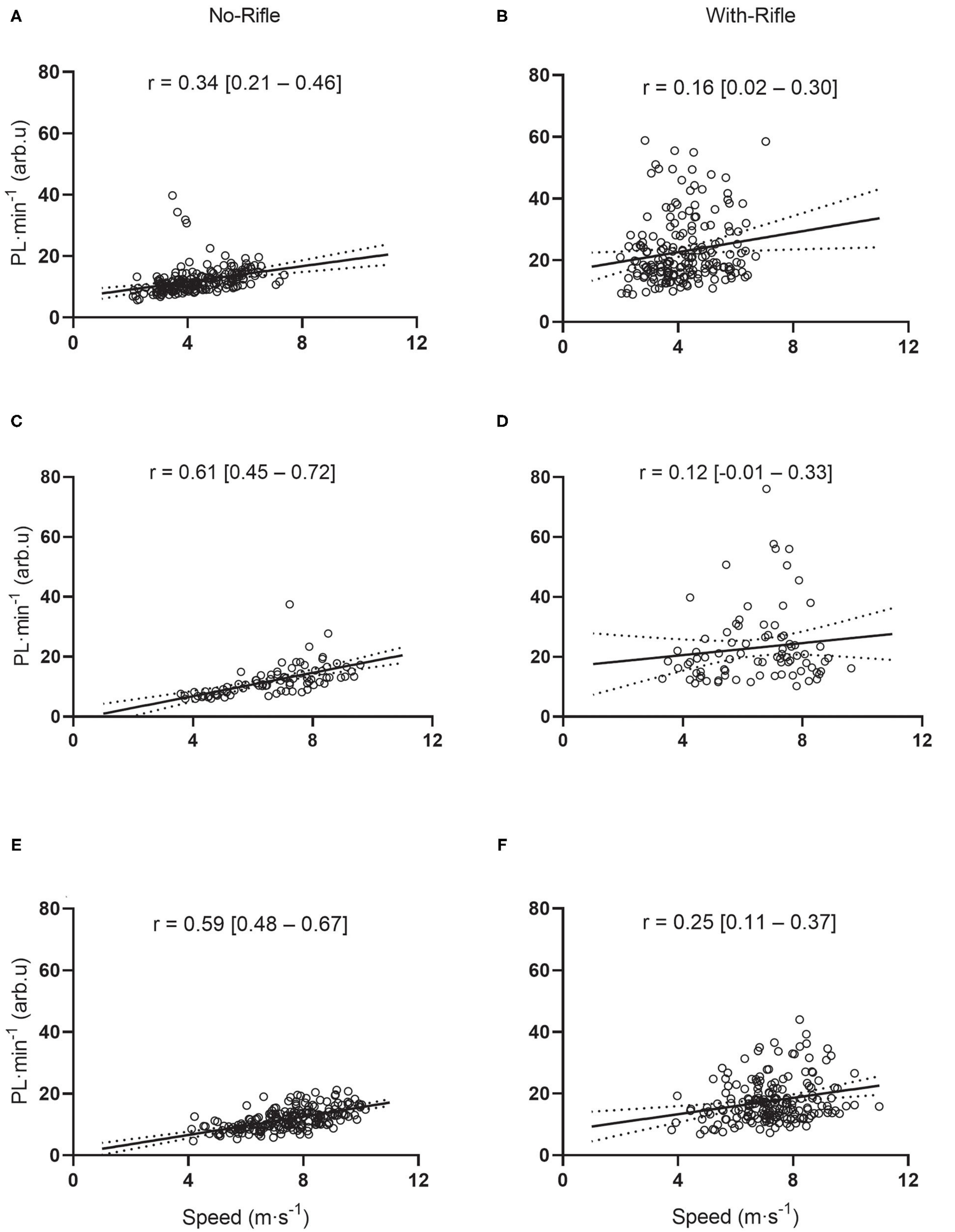

FIGURE 6 | Scatterplots displaying relationships between PlayerLoad^{TM} per minute and skiing speed during Uphill, Flat and Downhill gradients with and without the biathlon rifle. Each dot represents an individual speed (x) vs. PlayerLoad^{TM} per minute (y) (for the pelvis sensor) for every Uphill **(A,B)**, Flat **(C,D)** and Downhill **(E,F)** section. Panels on the left are for No-Rifle; Panels on the right are for With-Rifle. Pearson correlation coefficient (*r*) with 95% confidence interval shown.

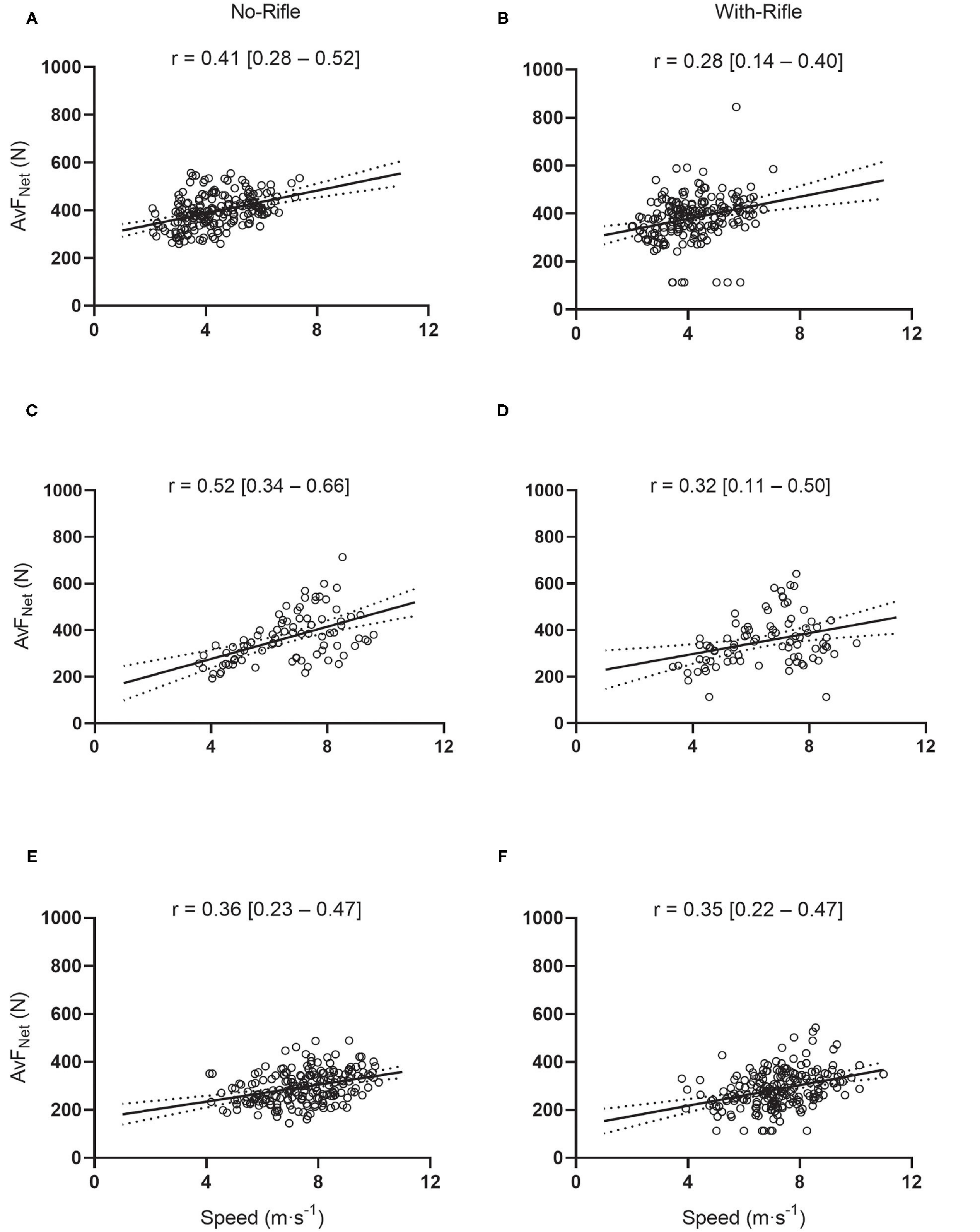

FIGURE 7 | Scatterplots displaying relationships between Average Net Force and skiing speed during Uphill, Flat and Downhill gradients with and without the biathlon rifle. Each dot represents an individual speed (x) vs. Average Net Force (y) (for the pelvis sensor) for every Uphill **(A,B)**, Flat **(C,D)** and Downhill **(E,F)** section. Panels on the left are for No-Rifle; Panels on the right are for With-Rifle. Pearson correlation coefficient (*r*) with 95% confidence interval shown.

Bla were elevated as a result of rifle carriage. However, the rifle impacted skiing time-trial performance, indicating the rifle impacted relative physiological intensity; (2) the magnitude of accelerometry-derived measures followed the expected response of exercise intensity during biathlon skiing; (3) significant positive linear relationships were identified between skiing speed and accelerometer-derived metrics during Uphill, Flat and Downhill skiing.

This study demonstrated that mean HR and Bla was not impacted by rifle carriage. However, it is not surprising that mean HR and Bla responses were not different given both time-trials (with and without rifle) were completed at maximum effort. Because rifle carriage significantly impacted the overall skiing time-trial performance in the present study, it can be concluded that rifle carriage did impact the relative physiological intensity. These findings confirm previous research where it was observed that rifle carriage increases metabolic work, HR and Bla during roller-skiing on a treadmill (Rundell and Szmedra, 1998; Stöggl et al., 2015; Jonsson Kårström et al., 2019). Further, the results of the present study extends previous research by demonstrating the physiological responses to biathlon skiing in a more ecologically valid, on-snow, setting.

This study identified that HR was greatest during the downhill sections of the skiing course and not during the flat or uphill sections. Similar research has also previously found average HR values to be the greatest during downhill sections of a skiing course (Bilodeau et al., 1991). This result might be explained by the methodological approach of averaging HR during each course gradient. In this particular course profile, downhill sections were preceded by an uphill section in nearly all cases. It is possible that other patterns could be observed if the course profile was different. Further, it is also possible that greater HR during downhill sections can be explained by the delay associated with cardiorespiratory acceleration and decelerations (Xu and Rhodes, 1999). It is common in biathlon and XC skiing for athletes to complete a high-intensity effort over the summit of each climb in order to maximize their momentum for the following downhill section (Ihalainen et al., 2022). This means that the HR response during the downhill sections might be reflecting the greater intensity during the preceding moments of high-intensity effort over the summit of each climb. Despite this potential limitation, HR is used almost exclusively as an indicator of exercise intensity during biathlon skiing (Kårström et al., 2021; Talsnes et al., 2021). It is acknowledged that measurement of the average exercise intensity from HR might still be useful because overestimation and underestimation of intensities over the duration of intermittent exercise might balance. However, it is likely that HR is not reflecting instantaneous exercise intensity, which might be important for an athlete to monitor within a training session or a race. Accordingly, novel methods of monitoring exercise intensity in skiing are warranted.

The magnitude of the accelerometry-derived metrics was typically greatest during uphill and flat sections and were lowest during downhill sections. This response likely resembles the actual external demands of the activity. Considering that the accelerometry-derived metrics represent dynamic bodily movements and not physiological demands, these results demonstrate that the bodily impacts and movement are still quite high during downhill sections. This is not surprising given downhill sections are associated with high speed turns and still require considerable expression of force to maintain body position, stability and velocity throughout a turn (Supej et al., 2011; Bucher Sandbakk et al., 2014; Sandbakk et al., 2014). Nevertheless, bodily movements and impacts remained greatest during uphill and flat sections where biathletes utilize different "gears" of skiing in order to best maintain a high speed over the duration of the course (Andersson et al., 2010). Utilization of these "gears" requires considerable use of dynamic bodily movements and hence high accelerometry-derived responses.

It is important to consider that this is the first study to use accelerometery-derived metrics to monitor the external demands in skiing. Currently, the only method of monitoring external intensity in skiing is through measuring skiing speed. It is acknowledged that locomotion speed is not necessarily the strongest indictor of external exercise intensity during skiing because different snow and weather conditions can greatly impact the skiing speed. Regardless, it is currently the only available measure of external exercise intensity practically available to skiers and coaches.

Significant positive linear relationships were identified between skiing speed and accelerometer-derived metrics during nearly all skiing sections. The one exception was an insignificant, small positive correction between PL$\cdot$min^{-1} and skiing speed during Flat sections With-Rifle. It is logical that there are positive associations between force (accelerations) and skiing speed during uphill sections because skiers utilize the aforementioned "gears" in order to generate propulsive forces to move themselves uphill against gravity (Gløersen et al., 2018; Swarén and Eriksson, 2019). Additionally, it is logical that high speeds during downhill and flat track sections are also associated with higher forces. As previously discussed, although downhill sections might be associated with little to no metabolic work, these sections are still associated with considerable expression of force (Supej et al., 2011; Bucher Sandbakk et al., 2014; Sandbakk et al., 2014). Interestingly, correlations between accelerometry-derived metrics and skiing speed were consistently stronger for No-Rifle compared to With-Rifle, particularly for PL$\cdot$min^{-1}. This might be explained be the fact that at the pelvis location (which is the location the correlations are derived from) PL$\cdot$min^{-1} was significantly greater with With-Rifle compared to No-Rifle (**Figure 4C**). In addition, the With-Rifle condition resulted in slower times (i.e., slower speeds) (**Table 1**). On the other hand, AvF_{Net} was more consistent across the With-Rifle and No-Rifle conditions.

This study has presented the utility of accelerometer-derived metrics during ecologically valid settings. Further investigation of the internal validity of these metrics is warranted by investigating during laboratory-controlled conditions, where accelerometry-derived metrics can be compared to measures of power output and internal physiological responses, such as $\dot{V}O_2$ and energy expenditure during standardized conditions. In particular, AvF_{Net} recorded at the Lower-Spine or Pelvis (i.e., sensor locations close to the center of mass) appears to be the most promising metric for measuring the external demand in XC skiing and biathlon. This is because the response at these two sensor locations followed the expected response, being greatest for Uphill, then Flat and lowest for Downhill sections. Additionally, rifle carriage had little impact on the magnitude of the AvF_{Net} response at these sensor positions, which also aligns with the physiological responses demonstrated in the present study. Further, the relationships between AvF_{Net} and skiing speed were far more consistent between With-Rifle and No-Rifle in comparison to $PL \cdot min^{-1}$. On the hand, it seems clear that $PL \cdot min^{-1}$ with sensor positions at the Lower-Spine and Pelvis, as well as AvF_{Net} recorded at the Upper-Spine are not suitable to determine the exercise intensity in biathlon. At these sensor locations there was a difference in PL between With-Rifle and No-Rifle conditions.

PRACTICAL APPLICATIONS

This research provides XC skiers, biathletes and their coaches with valuable information pertaining to the utility of physiological and accelerometry-derived metrics for monitoring exercise demands. Firstly, coaches and athletes need to recognize that HR does not necessarily reflect instantaneous exercise intensity, so caution must be used when interpreting these data at any given point in time. Regardless, HR might still provide useful information regarding average exercise intensity over the duration of a race or training session. Accelerometry-derived metrics might provide a method with utility for monitoring the external demands during biathlon and XC skiing. In particular, AvF_{Net} with sensors located close to the center of mass displayed greatest utility because it followed the expected response of external intensity where responses were greatest during uphill sections, followed by flats and lowest during downhills. In addition, there were significant positive relationships between AvF_{Net} and skiing speed ranging from small to large. AvF_{Net} has potential to be used in order to monitor the external demands during training and competition, as well as for the design of training programs to replicate competition intensities. However, further examinations are required before these metrics can be recommended for use in practice.

CONCLUSIONS

The biathlon rifle impacted skiing performance and the relative physiological intensity. In the present study HR was greatest during the downhill sections of the skiing course, which likely reflects the greater effort imposed during the preceding uphill. The accelerometry-derived approach used in this study provides the potential of a novel method of monitoring the external demands during skiing. In particular, AvF_{Net} recorded at the Lower-Spine or Pelvis (i.e., sensor locations close to the center of mass) appears to be the most promising metric for measuring the external demand in biathlon. Further research is required before AvF_{Net} can be recommended for use in practice.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Regional Ethical Board in Umeå, Sweden (#2016-506-31M). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CS participated in the design of the study, contributed to data collection and was responsible for data analysis, statistical analysis, and writing the manuscript. LS and MB participated in the design of the study and were responsible for data collection. MJ, ML, and GB participated in the design of the study and provided editorial assistance in manuscript preparation. All authors have read and approved the final version of the manuscript.

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The Determinants of Performance in Biathlon World Cup Sprint and Individual Competitions

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Purpose: The present study aimed to determine the association of skiing speed (SS), range time (RT), and the number of missed targets (MT) with rank in sprint and individual biathlon competitions.

Methods: Data were collected from the International Biathlon Union's database for 17 seasons (2002/2003–2018/2019). Furthermore, the biathletes were divided into three rank groups (G3, rank 1–3; G10, rank 4–10; and G20, rank 11–20). Multinominal regression was used to detect odds ratios associated with group rank for both sexes, separately.

Results: MT was the only variable that was constantly related to G3 (OR 1.90–6.35, all $p < 0.001$) for both women and men. SS was associated with G3 in the last lap in the sprint for both sexes (OR 0.46–0.66, all $p < 0.001$) and RT for standing shooting (OR 1.04–1.14, all $p < 0.05$).

Conclusion: These results show that shooting is the fundamental factor for performance in both competitions, but that SS is increasingly important for the last lap in the sprint for both sexes. Further, a fast RT in the standing shooting for women in individual and men in the sprint seems important for improving final rank.

Keywords: pacing, performance analysis, skiing, shooting, tactics

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INTRODUCTION

Biathlon is a complex winter sport consisting of cross-country skiing and rifle shooting, where several physiological (Rundell and Bacharach, 1995; Laaksonen et al., 2020), biomechanical (Sattlecker et al., 2014; Stöggl et al., 2015; Köykkä et al., 2021), and psychophysiological factors (Laaksonen et al., 2018) affect the performance. All these factors have an impact on the final rank, which is determined by skiing time (speed), shooting accuracy, and shooting time (speed). Biathletes compete in four different individual competition types (sprint, individual, pursuit, and mass start), which differ in skiing distance, number of shooting occasions as well as the order of shooting bouts. In addition, the starting procedure differs between these competition types, i.e., sprint and individual competitions have individual starts with a 30-s start interval between biathletes whereas in pursuit and, especially in mass start, the biathletes start at the same time. Thus, the different starting procedures may have an impact on tactical and pacing components between sprint and individual competitions in comparison to pursuit and mass start. Biathlon sprint (skiing distance 7.5 and 10 km for women and men, respectively) consists of three skiing laps interspersed by two shooting occasions, one in prone and one in standing position. On the other hand, in the individual competition (skiing distance 15 and 20 km for women and men, respectively), the biathlete skis five laps and has four shooting occasions (prone, standing, prone, and standing). In sprint, each missed target results in a penalty loop of 150 m (lasting ∼22–25 s), whereas in the individual competition, each missed target generates a 1-min penalty, which is added to the skiing and range times (RTs).

Earlier investigations have revealed that overall skiing speed (SS) has increased in biathlon pursuit and mass-start competitions since season 2002/2003 (Björklund et al., 2021). Moreover, there are some indications that SS also increased in sprint competitions (Laaksonen et al., 2018). However, the number of missed targets (MT) and the time spent on the shooting range (RT) have not changed in a similar fashion compared to SS (Björklund et al., 2021). In addition, the development of these variables in biathlon sprint and individual competitions is currently unknown. From another point of view, SS has been proposed, based on correlational methods, to be the major factor for performance in a sprint (Luchsinger et al., 2018; Dzhilkibaeva et al., 2019), followed by the number of MT. However, in individual competitions, the contribution from these factors for final performance is more or less even, with some differences between sexes (Luchsinger et al., 2019). Interestingly, the impact of RT on final performance seems to be minimal. Björklund et al. (2021) recently observed that the influence of SS during different skiing laps as well as MT and RT during different shooting occasions affects the final performance. This further indicates the importance of pacing in biathlon pursuit and mass-start competitions. However, the impact of SS, MT, and RT during different loops and shooting occasions has not been fully studied in biathlon sprint and individual competitions.

Therefore, the aim of the present study was first, to describe the development of SS, RT, and MT over different seasons, and second, to investigate the impact of SS, RT, and MT to final rank in biathlon sprint and individual competitions. The present study also aimed to investigate the impact of SS during different skiing loops as well as RT and MT during different shooting occasions on the final rank more in detail. Based on earlier research, we hypothesized that in biathlon sprint, SS followed by MT are the most important factors for final rank, whereas RT plays a minor role. In addition, it was hypothesized that in individual competition SS and MT have a similar impact on final rank, and again, RT plays a minor role.

METHODS

All data were obtained from the International Biathlon Union's (IBU) datacentre, which is an openly available public domain at http://www.biathlonresults.com (International Biathlon Union, 2019) and permission was granted from IBU to use the data for scientific purposes. Data were collected for biathletes ranked 1–20 in all single sprint and individual IBU World cup competitions during the 2002/2003–2018/2019 seasons ($n = 17$ seasons). The number of sprint competitions per season was nine during seasons 2002/2003, 2015/2016–2018/2019 and 10 during seasons 2003/2004–2014/2015 and 2018/2019. Similarly, the number of individual competitions was two during seasons 2018/2019, three during seasons 2002/2003–2003/2004, 2005/2006, 2007/2008, 2011/2012–2017/2018, and four during seasons 2004/2005, 2006/2007, 2008/2009–2010/2011. The number of unique starts for the sprint was as follows: women $n = 3{,}245$ and men $n = 3{,}264$, and for the individual start, women $n = 1{,}041$ and men $n = 1{,}073$. The biathletes were further categorized into three groups separately for women and men based on their final rank in each separate competition (G3, rank 1–3; G10, rank 4–10; and G20, rank 11–20). The data were then split based on the event and checked for outliers, where any results differing more than 1.5 times the interquartile range from the mean were removed from the dataset. Thus, missing values, e.g., due to lost sensor connection or timing transponder were excluded.

Data and Statistical Analysis

All data were pre-checked for normality using the Kolmogorov–Smirnov test. SS, RT, and MT did not conform to normal distribution. Consequently, a multi-nominal regression was used to investigate the association between SS, RT, and MT to group rank (G3, G10, and G20). For more exact comparisons, skiing time was converted to SS due to variations in the distance for the skiing tracks used by IBU. The SS for each lap was calculated as the distance of each lap divided by the skiing time for the lap, and similarly, the total SS was calculated as the total skiing distance for competition divided by the total skiing time. The analyses were performed using separate models for sprint and individual starts for women and men separately. The reference group, i.e., the base category that all other groups are related to, was set to G3 for both types of events. Comparisons between SS within sprint and individual events for women and men were analyzed using a Friedman's test to compare the laps (3 and 5 per event for SS), and RT and MT per shooting occasion for the individual competition (4 occasions per event). A Durbin Conover test was applied if Friedman's test was significant to make pairwise comparisons. A Wilcoxon signed ranked test was used to compare RT and MT in the sprint event (2 occasions per event). A point biserial correlation (r_{pb}) coefficient was used as the effect size. Interpretive benchmarks were small $r_{pb} < 0.10$, medium $r_{pb} = > 0.11–< 0.36$, and large $r_{pb} > 0.37$ (McGrath and Meyer, 2006). Kruskal–Wallis non-parametric test was used to compare the seasons for SS (2003–2019) and RT (2012 2019) with an epsilon squared (ε^2) for the determination of the effect size. The measurement of RT became standardized from season 2011/2012, and therefore, the use of data before that season was not reliable. Furthermore, a Dwass-Steel-Critchlow-Flinger test was applied for pairwise comparisons if there was a global significance for the Kruskal–Wallis test. For comparisons between groups related to the number of MT, a χ^2 test of independence was applied. A Cramer's V (V) was used for effect size. MT are presented as numbers and modes. Statistical analyses were performed using *jamovi* (The Jamovi Project, 2020) and SPSS statistical package version 27 (SPSS Inc. Chicago, IL; the normality check) with data presented as odds ratios (OR) with confidence intervals (95% Cl), median (interquartile range [IQR]), or mean values, where appropriate. The α was set *a priori* to <0.05.

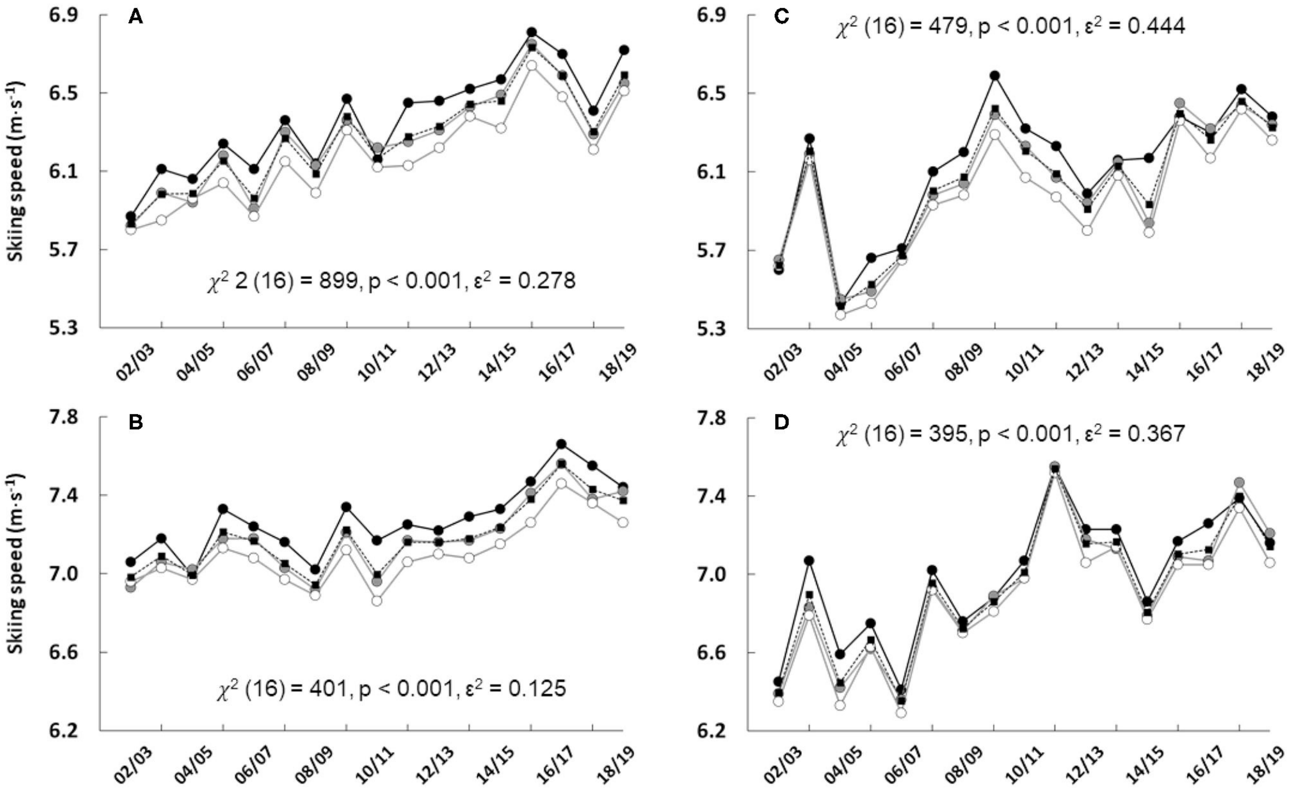

FIGURE 1 | The skiing speed in sprint and individual competitions for women [**(A)** and **(C)**, respectively] and men [**(B)** and **(D)**, respectively] including the overall (black dashes line, black squares) and groups of ranks 1–3 (black solid line, black filled circles), ranks 4–10 (gray solid line, gray filled circles), and ranks 11–20 (gray solid line, white filled circles) during seasons from 2002/2003 to 2018/2019. Each data point represents the median of all competitions during each season for each group. Sprint **(A,B)** and individual **(C,D)** include 9–10 and 3–4 competitions during each season, respectively, except season 2018/2019 having only 2 individual competitions.

RESULTS

Skiing Speed

Over the 17 seasons of this analysis, for both sprint and individual competitions, SS increased from 2002/2003 to 2018/2019 ($p < 0.001$) for both women and men. There was a substantial year-to-year variability, as shown in **Figures 1A–D**.

In the sprint, SS changed between laps, with the first lap being the fastest for both women and men [women = 6.34 (5.87–6.72) $m{\cdot}s^{-1}$, **Figure 2A**; men = 7.35 (7.03–7.63) $m{\cdot}s^{-1}$, **Figure 2B**] and the second lap the slowest [women = 6.19 (5.85–6.51) $m{\cdot}s^{-1}$; men = 7.11 (6.81–7.35) $m{\cdot}s^{-1}$]. In both women's and men's sprint races, G3 was strongly associated with faster SS during the second lap compared to G20, and during the last lap compared to both G10 and G20 (**Table 1**).

In the individual start, SS resembled the same pattern for both women and men with the first lap being the fastest [women = 6.24 (5.81–6.56) $m{\cdot}s^{-1}$, **Figure 2C**; men = 7.03 (6.72–7.54) $m{\cdot}s^{-1}$; **Figure 2D**] and the fourth lap being the slowest [women = 5.95 (5.61–6.25) $m{\cdot}s^{-1}$; men = 6.75 (6.39–7.05) $m{\cdot}s^{-1}$]. In the women's individual competition, a faster SS was only associated with rank during the first lap (G20 vs. G3, $p = 0.011$). There were no associations between SS and rank in all the other laps (**Table 1**). In the men's individual competition, the last lap was associated with G3 in comparison to G20 ($p = 0.019$; **Table 1**).

Range Time

As can be seen in **Figure 3**, RT varied substantially between seasons for both women (**Figures 3A,C**) and men (**Figures 3B,D**). Consequently, there were no trends for an overall faster RT for either women or men from 2011/2012 to 2018/2019 in sprint or individual competitions.

For the sprint event, RT was fastest during the standing shooting [women = 51.6 (48.1–55.2) s; men = 46.4 (43.4–49.6) s] and slowest during the prone shooting [women = 53.7 (49.9–57.4) s; men = 49.7 (46.6–53.1) s] for both women and men [$z = 14.8$, $p < 0.001$, $r_{pb} = 0.445$ and $z = 26.0$, $p < 0.001$, $r_{pb} = 0.686$, respectively]. A fast RT during standing shooting in the women's sprint was associated with G3 compared to G20 ($p = 0.020$; **Table 2**). Similarly, in the men's sprint competition, a fast RT during standing shooting was associated with rank (G3 vs. G10, $p < 0.001$; G3 vs. G20, $p < 0.001$; **Table 2**).

In the individual event, RT changed between shooting bouts with the second occasion (first standing) being the fastest [women = 51.9 (48.5–55.6) s; men = 47.2 (44.2–50.4) s] and the third shooting occasion (second prone) being the slowest

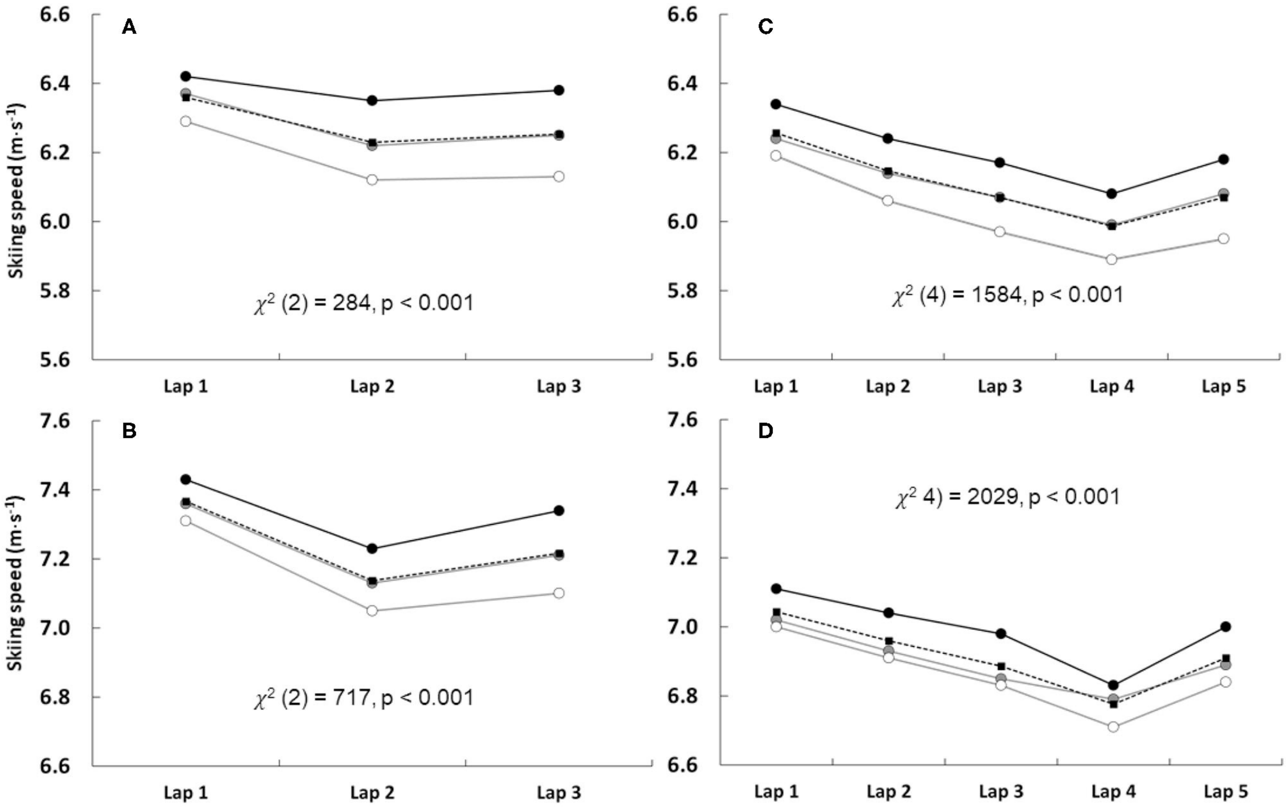

FIGURE 2 | The skiing speed during different laps in sprint and individual competitions for women [**(A)** and **(C)**, respectively] and men [**(B)** and **(D)**, respectively], including the overall (black dashed line, black squares) and groups of ranks 1–3 (black solid line, black filled circles), ranks 4–10 (gray solid line, gray filled circles,) and ranks 11–20 (gray solid line, white filled circles) during seasons from 2002/2003 to 2018/2019. Each data point represents the median of all competitions during each season for each group. Sprint **(A,B)** and individual **(C,D)** include 9–10 and 3–4 competitions during each season, respectively, except season 2018/2019 having only 2 individual competitions.

[women = 56.8 (53.2–60.6) s; men = 52.9 (50.0–56.2) s] for both women and men [$\chi^2_{(3)} = 373$, $p < 0.001$, $\chi^2_{(3)} = 515$, $p < 0.001$, respectively]. In the women's individual competition, a fast RT at the second shooting occasion (first standing) was associated with rank (G3 vs. G10, $p = 0.009$; G3 vs. G10, $p = 0.049$; **Table 2**). For the men in the individual competition, a fast RT was associated with rank during the last prone (G3 vs. G10, $p = 0.007$; G3 vs. G20, $p = 0.036$; **Table 2**) and standing shooting (G3 vs. G10, $p = 0.045$; **Table 2**).

Shooting Profile

The total numbers of the most frequent MT during the sprint start were for women: G3 = 0–1; G10 = 0–1; G20 1–2 and for men: G3 = 0–1; G10 = 0–1; G20 1–2 (**Table 3**). The most frequent total numbers of MT during the individual start were for women: G3 = 0–1; G10 = 1–2; G20 2–3 and for men: G3 = 0–1; G10 = 1–2; G20 2–3 (**Table 3**).

In the women's sprint competition, the MT values (min–max) for in prone and standing, shooting, respectively, were for G3 (0–2 and 0–3), G10 (0–3 and 0–3), and G20 (0–3 and 0–5). For men, the MT values (min–max) in prone and standing shooting, respectively, were for G3 (0–2 and 0–3), G10 (0–3 and 0–4), and G20 (0–4 and 0–4).

In the individual competition for women, the MT values (min–max) in the two-prone and two-standing shooting, respectively, were for G3 (0–1, 0–1, 0–2, and 0–2), G10 (0–3, 0–2, 0–4, and 0–4), and G20 (0–4, 0–4, 0–3, and 0–3). For men in the individual competition the MT values (min-max) in the two-prone and two-standing shooting, respectively, were for G3 (0–1, 0–2, 0–2, and 0–2), G10 (0–3, 0–2, 0–3, and 0–3), and G20 (0–3, 0–3, 0–4, and 0–3).

In the sprint, both women and men showed a greater number of MT during the standing than prone shooting ($z = 13.8$, $p < 0.001$, $r_{pb} = 0.330$ and $z = 12.6$, $p < 0.001$, $r_{pb} = 0.306$, respectively). Overall, in the women's and men's individual competitions, there was a greater number of MT in the two-standing vs. the prone shootings [$\chi^2_{(3)} = 150$, $p < 0.001$ and $\chi^2_{(3)} = 110$, $p < 0.001$, respectively]. There were no differences in MT between the standing or the prone shooting for either women or men ($p = 0.818$ and $p = 0.601$), although there was a trend for a greater number of MT during the first vs. the second prone shooting occasion for women (women $p = 0.055$ and men

TABLE 1 | Multi-nominal logistic regression for skiing speed in women's and men's sprint and individual competitions in IBU WC 2002/2003–2018/2019.

Sprint-start	Women			Men		
Group	**OR**	**95% CI**	***p*-value**	**OR**	**95% CI**	***p*-value**
G10–G3						
Lap 1	1.24	0.87–1.78	=0.241	1.07	0.74–1.56	=0.716
Lap 2	0.66	0.39–1.11	=0.114	0.70	0.43–1.14	=0.153
Lap 3	0.66	0.48–0.91	=0.010	0.65	0.47–0.91	=0.012
G20–G3						
Lap 1	1.37	0.97–1.93	=0.079	1.37	0.96–1.96	=0.087
Lap 2	0.48	0.29–0.80	=0.005	0.48	0.30–0.77	=0.002
Lap 3	0.49	0.36–0.66	<0.001	0.46	0.34–0.64	<0.001
Individual-start	**Women**			**Men**		
G10–G3						
Lap 1	1.74	0.66–4.57	=0.263	1.22	0.48–3.08	=0.674
Lap 2	1.19	0.08–16.71	=0.900	2.47	0.25–24.15	=0.438
Lap 3	0.73	0.03–20.07	=0.849	0.13	0.01–1.95	=0.140
Lap 4	0.45	0.03–6.32	=0.552	3.36	0.37–30.59	=0.282
Lap 5	0.84	0.41–1.71	=0.631	0.59	0.28–1.22	=0.151
G20–G3						
Lap 1	3.36	1.32–8.54	=0.011	1.42	0.58–3.46	=0.443
Lap 2	1.74	0.14–22.28	=0.672	6.74	0.75–60.65	=0.089
Lap 3	0.13	0.01–3.14	=0.206	0.24	0.02–3.19	=0.278
Lap 4	0.77	0.06–9.91	=0.838	0.60	0.07–4.96	=0.637
Lap 5	0.55	0.28–1.09	=0.089	0.44	0.22–0.87	=0.019

Lap: G3, rank 1–3; G10, rank 4–10; G20, rank 11–20. Data are reported as odds ratio (OR) with a 95% confidence interval (95% CI) and p-values.

$p = 0.103$). The ORs for the shooting bouts in sprint and the individual starts are presented in **Table 4**.

Between seasons from 2002/2003 to 2018/2019, the number of total MT in the sprint differed for both women [$\chi^2_{(16)} = 69.2$, $p < 0.001$, $\varepsilon^2 = 0.0213$] and men [$\chi^2_{(16)} = 50.2$, $p < 0.001$, $\varepsilon^2 = 0.0154$]. There were no clear patterns in shift in MT between different time periods in the sprint competitions for women or men. In the individual event, there was an overall change in MT for women [$\chi^2_{(16)} = 104$, $p < 0.001$, $\varepsilon^2 = 0.100$] and men [$\chi^2_{(16)} = 53.4$, $p < 0.001$, $\varepsilon^2 = 0.0498$]. In 2017/2018–2018/2019, there were significantly fewer MT compared to 2002/2003–2005/2006 in the women's individual competition ($p < 0.001$). In the men's individual competition there was no clear shift between time periods for MT.

DISCUSSION

Partly against our hypothesis, the main finding of the present study identified that the number of MT is the fundamental variable for success within the top 20 biathletes in both sprint and individual competitions in biathlon. This pattern is recurrent for both women and men on all shooting occasions and demonstrates that podium-placed biathletes typically prevail over the top 10 and 20 athletes due to more accurate shooting. Moreover, in the sprint event, fast SS is important for both women and men and shows a strong association to a podium rank. Additionally, a fast RT seems more important for performance in the sprint for men compared with women. In the individual start, a fast RT for women in the first standing shooting influences the final rank, whereas SS has a minor impact only.

In general, the present results show a significant increase in total SS over the studied seasons. On average, SS in biathlon sprint has increased by ∼4 and 2% per 5-year period for women and men, respectively. Similarly, in individual competitions, both sexes demonstrated an increased SS of ∼4% per 5-year period. This finding is in-line with earlier investigations which showed increases in SS in sprint (Laaksonen et al., 2018) as well as in pursuit and mass-start competitions (Björklund et al., 2021), and is likely due to the development of skiing material as well as course preparation. Interestingly, in individual competitions, it seems that there is more variation in the development of SS in comparison to sprint. This can be partly explained by the small number of individual competitions per season (2–4) compared to sprint, with 9 or 10 per season. The variation can also be due to changes in weather conditions between seasons, which may affect the overall SS.

Variation in SS between different laps (i.e., pacing), both in sprint and individual competitions, followed a typical J-shaped curve as also has been seen earlier in biathlon (Luchsinger et al., 2019; Björklund et al., 2021). In general, the present study identified that G3 biathletes had faster SS, as shown

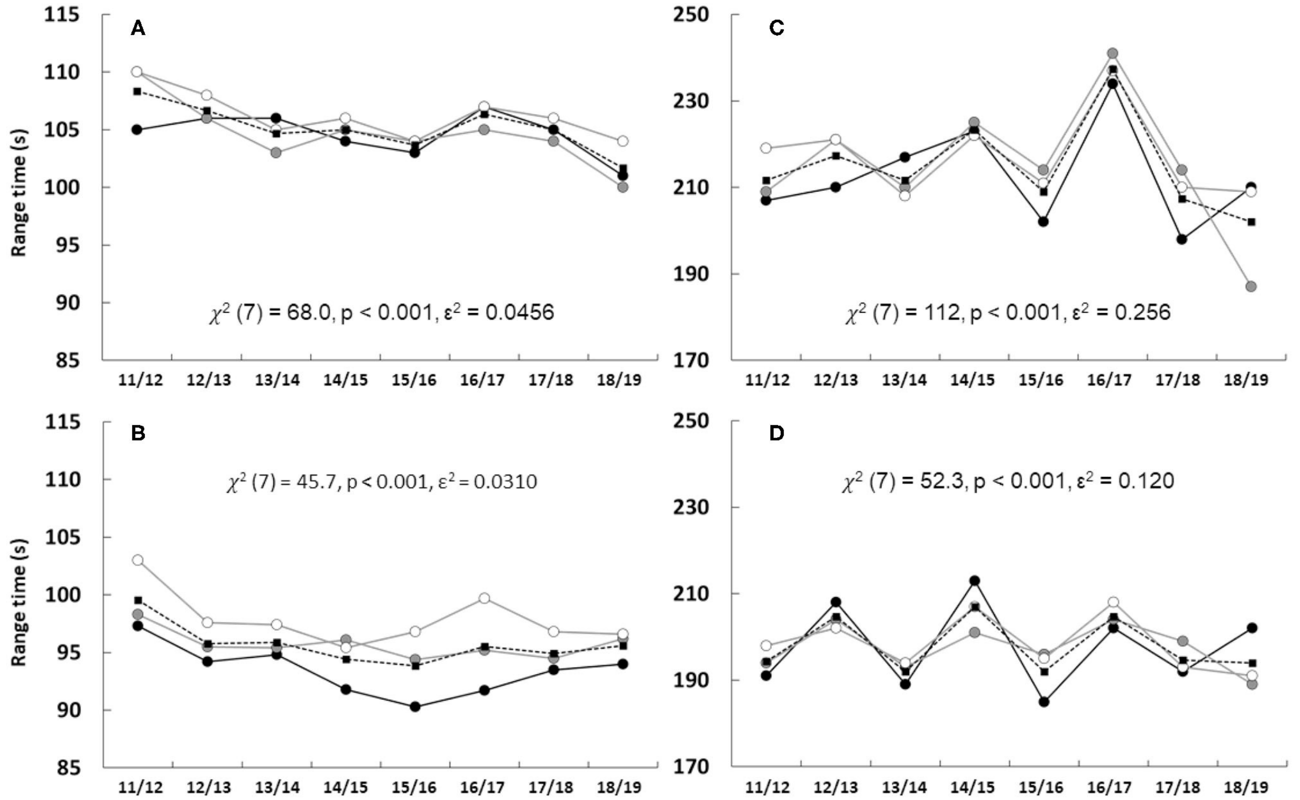

FIGURE 3 | The total range time in sprint and individual competitions for women [**(A)** and **(C)**, respectively] and men [**(B)** and **(D)**, respectively] including the overall (black dashed line, black squares) and groups of ranks 1–3 (black solid line, black filled circles), ranks 4–10 (gray solid line, gray filled circles) and ranks 11–20 (gray solid line, white filled circles) during seasons from 2002/2003 to 2018/2019. Each data point represents the median of all competitions during each season for each group. Sprint **(A,B)** and individual **(C,D)** include 9–10 and 3–4 competitions during each season, respectively, except season 2018/2019 having only 2 individual competitions.

in **Figures 1**, **2**, but that likelihood with higher SS to be ranked in G3 was not that obvious than in an earlier study of biathlon pursuit and mass-start competitions (Björklund et al., 2021). Indeed, in sprint, a faster SS was associated with G3 only during the second (compared to G20) and third (both G10 and G20) laps, whereas in pursuit and mass-start competitions a higher SS was associated with podium rank during almost all the five laps (Björklund et al., 2021). Thus, in biathlon sprint, SS is an important factor for final rank, but other factors, such as RT and MT, may also play a more important role than previously suggested, at least in top 20 ranked biathletes. In contrast to sprint, in individual competitions, SS during different laps had very little impact on the final rank. Indeed, only the last lap for men had an association favoring G3 compared to G20. This observation supports the earlier investigation related to biathlon individual competition where penalty time (i.e., shooting accuracy) explained ∼50% of the performance difference between 1–10 and 21–30 ranked biathletes (Luchsinger et al., 2019).

Range time showed a considerably larger variation between seasons for individual compared to sprint competition. It is unlikely that this variation is related to biathletes' capability in shooting. It can be speculated that this is because there are usually only three individual competitions during each season (compared to nine sprint competitions), therefore, changes, e.g., in weather conditions or different venues make RT more sensitive in this regard. However, RT was associated with the podium-placed athletes, especially in the sprint competition for the men. Previous research comparing groups from top 10 to 21–30 ranked biathletes (seasons 2011/2012–2015/2016) has shown a very low explanatory level for both sprint and individual competition for both sexes (Luchsinger et al., 2018, 2019). While the current study used top 20 athletes, it indicates that RT during the standing shooting plays an important role for the men in sprint. RT seems to be an important factor to be ahead in both G10 and G20 groups, and likely greater than the 2% explanatory factor previously shown for biathletes ranked further apart (Luchsinger et al., 2018). In the individual competition for women, a faster RT in the first shooting improves the odds to end up in G3. Interestingly, in the men's individual competition a faster RT in the second prone shooting is associated with a poorer rank. In contrast to what seems obvious as a faster RT that should be in favor of a better rank, this is in reversed order. Possibly, the

TABLE 2 | Multi-nominal logistic regression for range time in women's and men's sprint and individual competitions in IBU WC 2002/2003–2018/2019.

Sprint-start	**Women**			**Men**		
Group	**OR**	**95% CI**	***p*-value**	**OR**	**95% CI**	***p*-value**
G10–G3						
RT 1	0.98	0.94–1.01	=0.220	0.96	0.92–1.00	=0.054
RT 2	1.02	0.99–1.06	=0.246	1.09	1.04–1.14	<0.001
G20–G3						
RT 1	1.00	0.97–1.04	=0.983	0.975	0.94–1.01	=0.182
RT 2	1.04	1.01–1.08	=0.020	1.136	1.09–1.19	<0.001
Individual-start						
G10–G3						
RT 1	0.93	0.85–1.02	=0.145	1.08	0.98–1.19	=0.132
RT 2	1.13	1.03–1.24	=0.009	1.03	0.93–1.13	=0.590
RT 3	1.02	0.92–1.12	=0.737	0.87	0.79–0.96	=0.007
RT 4	0.96	0.89–1.03	=0.272	1.09	1.00–1.19	=0.045
G20–G3						
RT 1	0.96	0.88–1.05	=0.373	1.04	0.95–1.15	=0.383
RT 2	1.09	1.00–1.19	=0.049	1.05	0.96–1.16	=0.290
RT 3	1.01	0.92–1.10	=0.834	0.90	0.82–0.99	=0.036
RT 4	0.99	0.92–1.06	=0.688	1.07	0.99–1.17	=0.092

RT, range time; G3, rank 1–3; G10, rank 4–10; G20, rank 11–20. Data are reported as odds ratio (OR) with a 95% confidence interval (95% CI) and p-values.

TABLE 3 | Frequency of missed targets out of the total number fired shots in sprint and individual competitions in IBU WC 2002/2003–2018/2019.

Sex	**Group**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Total**
Sprint-start (total number of fired shoots *n* = 32 450)										
W	G3	**287 (59%)**	158	40	2	1	0	0	0	488
	G10	411	**490 (43%)**	194	37	4	1	0	0	1,137
	G20	351	**705 (43%)**	410	129	23	0	2	0	1,620
	Total	1,049	1,353	644	168	28	1	2	0	3,245
		χ^2 (12, N = 3,245 = 312, p < 0.001, V = 0.225)								
Sprint-start (total number of fired shoots *n* = 32 640)										
M	G3	**297 (61%)**	153	32	7	0	0	0	0	489
	G10	429	**518 (45%)**	161	38	1	1	0	0	1,148
	G20	376	**698 (43%)**	406	123	24	0	0	0	1,627
	Total	1,102	1,369	599	168	25	1	0	0	3,264
		χ^2 (10, N = 32,64 = 331, p < 0.001, V = 0.225)								
Individual-start (total number of fired shoots *n* = 20 820)										
W	G3	55	**65 (41%)**	32	5	0	0	0	0	157
	G10	40	123	**126 (35%)**	50	20	5	0	0	364
	G20	33	116	**157 (30%)**	137	55	17	4	1	520
	Total	128	304	315	192	75	22	4	1	1,041
		χ^2 (14, N = 1,041 = 183, p < 0.001, V = 0.297)								
Individual-start (total number of fired shoots *n* = 21 460)										
M	G3	48	**84 (52%)**	27	2	0	0	0	0	161
	G10	47	**157 (41%)**	124	42	5	1	0	0	376
	G20	20	122	**200 (37%)**	139	51	4	0	0	536
	Total	115	363	351	183	56	5	0	0	1,073
		χ^2 (10, N = 1073 = 235, p < 0.001, V = 0.331)								

W, women; M, men; G3, rank 1–3; G10, rank 4–10; G20, rank 11–20. Bold numbers represent mode (percent) for each group and sex.

TABLE 4 | Multi-nominal logistic regression for missed targets in women's and men's sprint and individual competitions in IBU WC 2002/2003–2018/2019.

Sprint-start	Women			Men		
Group	**OR**	**95% CI**	***p*-value**	**OR**	**95% CI**	***p*-value**
G10–G3						
1st prone shooting	2.03	1.60–2.58	<0.001	2.02	1.590–2.57	<0.001
1st standing shooting	1.97	1.62–2.38	<0.001	1.90	1.560–2.30	<0.001
G20–G3						
1st prone shooting	3.21	2.55–4.04	<0.001	3.15	2.490–3.97	<0.001
1st standing shooting	3.07	2.55–3.70	<0.001	3.21	2.660–3.88	<0.001
Individual-start	**Women**			**Men**		
G10–G3						
1st prone shooting	2.47	1.60–3.81	<0.001	2.86	1.76–4.63	<0.001
1st standing shooting	2.92	1.79–4.78	<0.001	2.36	1.48–3.77	<0.001
2nd prone shooting	2.12	1.50–3.01	<0.001	2.20	1.54–3.16	<0.001
2nd standing shooting	2.19	1.56–3.09	<0.001	2.06	1.43–2.96	<0.001
G20–G3						
1st prone shooting	3.37	2.19–5.18	<0.001	6.35	3.91–10.31	<0.001
1st standing shooting	4.08	2.51–6.65	<0.001	4.38	2.74–6.99	<0.001
2nd prone shooting	3.31	2.34–4.67	<0.001	4.14	2.88–5.97	<0.001
2nd standing shooting	3.28	2.34–4.61	<0.001	4.88	3.38–7.04	<0.001

Shooting; G3, place 1–3; G10, place 4–10; G20, place 11–20. Data are reported as odds ratio (OR) with a 95% confidence interval (95% CI) an p-values.

biathletes ranked outside the top 10 rush the shooting pace to make up time as they might be behind due to poor shooting and slow SS. Nevertheless, the current study is in agreement with a previous analysis in individual competitions in biathlon (Luchsinger et al., 2019) that RT has a rather small impact on the final rank.

Overall, the number of MT was the central variable that was constantly associated with group ranking in both sprint and individual events. The podium-ranked group (G3) constantly displayed fewer MT in prone and standing shooting. Accordingly, in sprint, both sexes demonstrated that for both prone and standing shooting fewer MT doubles the likelihood to be placed in G3 compared to G10. In the individual competition, biathletes were almost three times more likely to be placed in G3 compared to G10, independent of sex, with fewer MT. This indicates that shooting performance is even more important in the individual race compared to the sprint competition. This is in-line with previous reports where shooting accuracy (i.e., MT) has been suggested to explain ∼50% of the final rank in individual competition (Luchsinger et al., 2019), whereas in sprint, shooting accuracy explains ∼30% with remaining ∼60% explained by SS (Luchsinger et al., 2018; Dzhilkibaeva et al., 2019). However, the compared groups in studies by Luchsinger et al. (2018) were further apart (1–10 vs. 20–30) compared to the current study using clusters within the top 20.

Overall, there is one clear distinction in the frequency of the number of MT between sprint and the individual start. Most often the podium-placed group for both sexes in the sprint event display zero MT, while in the individual start the number of MT is most often one. For the sprint, this is in agreement with previously published data that showed that winners in the sprint event demonstrate a pattern of zero MT (Björklund, 2018). However, in both the sprint and the individual competitions, there are rare cases where biathletes placed on the podium have as many as 3–4 MT, and in those cases, it is likely due to difficult environmental conditions. Additionally, the difference between group ranks (i.e., G3, G10, and G20) in both competition types and sexes shows that there is an overlap in MT between groups. This is different compared to pursuit and mass-start events that instead show a clear pattern of one extra MT between ranked groups of G3, G10, and G20 (Björklund et al., 2021). Interestingly, it has been proposed that without taking final rank into account, the biathlon sprint has the overall lowest hit rate compared to other events (Maier et al., 2018). This is in complete contrast to another study suggesting that when adding the final rank into account, the podium group shows the lowest number of MT in all events (Björklund et al., 2021), which is supported by the recent findings. Nonetheless, in accordance with previous research, the standing shooting seems to be the most difficult of the two as it displays the greatest number of MT for both women and men (Maier et al., 2018).

One limitation of the present study is the lower number of individual competitions per season in comparison to sprint. This may partly explain the larger variation in SS and RT between seasons together with the fact that the present study did not take weather conditions into account. Also, the venues for individual competitions were likely to differ more between seasons compared to sprint (nine to 10 competitions at 10 different venues), which implies in practical terms that most of the sprint competitions were held at the same venue during each season.

CONCLUSION

In all, the central performance variable between athletes within the top 20 for both women and men is to reduce the number of MT. This holds true for both the sprint and individual competitions. Furthermore, in the sprint competition, SS is important to increase the possibility to be placed in a better-ranked group, especially during the second and third lap. Moreover, to be placed in the podium group in the sprint competitions, RT is essential at the standing shooting, especially for the men. In the individual start, women seem to benefit from a faster RT during the standing shooting.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants, in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

GB and ML designed and analyzed the data, interpreted the data, wrote the first draft of the manuscript, and drafted the final manuscript and approve the final version to be published and agree to be accountable for all aspects of the work.

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ORIGINAL RESEARCH
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How Does the Starting Order in the First and Second Run Affect the Final Rank in the FIS World Cup Giant Slalom?

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The aim of this study was to determine the impact of runs 1 and 2 on overall rank in Giant Slalom. Data from 15 seasons (2005/2006–2019/2020) including and unique starts for women ($n = 2{,}294$) and men ($n = 2{,}328$) were analyzed. Skiers were grouped based on final ranks 1–3 (G3), 4–10 (G10), and 11–20 (G20) and separately analyzed for women and men. A Wilcoxon-signed rank test was used for comparisons between runs 1 and 2, while a multi-nominal logistic regression was used to identify odds ratios (OR) associated with group rank. Women had similar run times for runs 1 and 2 ($p = 0.734$), while men had faster times on run 2 ($p < 0.001$). The strongest association to G3 was during run 1 for run time (men: OR 1.06–1.12; women: OR 1.06–1.11, all $p < 0.01$) and gate-to-gate times (men: OR 33–475; women: OR 81–2,301, all $p < 0.001$). Overall, this study demonstrates the importance of a fast first run for improving the final ranking group and the need to increase the tempo going from the first to the second run for men.

Keywords: alpine skiing, race tactics, performance analysis, winter sports, elite sports

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INTRODUCTION

The difference among Alpine World Cup (WC) skiers is often only a few hundredths of a second; however, there are shorter sections along the courses where the differences can vary by 10% (Supej and Cernigoj, 2006b; Supej et al., 2011). A detailed performance analysis can be obtained by comparing gate-to-gate times, which is the time taken to pass between each gate of the course (Supej and Cernigoj, 2006b; Swarén et al., 2021). This can be considered as the skier's tempo that changes depending on the steepness of the terrain, the skiing speed, the course setting, and the skier's skill level. There are two main strategies to achieve high-level race performance (i) continuously aim for short section times over several consecutive sections or (ii) target a high-velocity gain resulting in a shorter time in the subsequent section (Supej and Cernigoj, 2006b; Spörri et al., 2012, 2018).

Although Spörri et al. (2018) show it is of a higher priority to maintain skiing speed than shortening the center of mass path length, a bad snow surface is likely to affect both and ultimately have a large negative impact on performance overall. Previous studies have shown skiing performance can be affected by changing conditions of the ski courses, especially in steeper sections of the course, and therefore the start order can significantly influence the skier's final ranking (Supej et al., 2005; Lešnik et al., 2013). A Giant Slalom race (GS) in alpine skiing consists of two different runs whereby the top 30 skiers in the first run qualify for the second, with the final race result being the combined time of both. For the first run, the starting order is drawn based on skiers' ranking points set by the International Ski Federation (FIS) (Maisano et al., 2016). The top 30 skiers are then divided into three groups where the top seven GS skiers draw for the start numbers 1–7, the second group for the start numbers 8–15, and the third group 16–30 (FIS, 2019/2020). With a high starting number, previous skiers have already indented the snow surface thus it is often more difficult to choose and maintain an individual line through the course. Therefore, the starting order in the second run is reversed whereby the skier who finished 30th in the first run begins the second run.

As skiing performance is affected by starting order and changing ski course conditions, and the reversed start order in the second run should allow slower skiers in the first run to make up time. However, it is likely that the slower skiers in the first run are ranked lower and therefore are less skilled in comparison to those in the starting group 1–7. Nevertheless, the reversed starting order also provides a good opportunity to reduce the time differences among the fastest skiers, as well as those in the starting group who may have executed a poor first run.

Despite the obvious importance of final rank and overall performance in GS, the influence of the starting order in GS has not yet been investigated. Consequently, knowledge regarding the importance of the different starting groups, as well as of whether male and female skiers are similarly affected by the starting order is lacking. Hence, this study aims to analyze the associations between (i) the starting order and the race result and (ii) the likelihood to make up time in the second run after a poor first run among men and women competing in FIS World Cup in Giant Slalom over several seasons.

METHODS

All race data were obtained from the International Ski Federation's (FIS) datacenter, an open public domain (www.fis-ski.com). Specifically, data were collected from the top 20 skiers who completed the second run of a WC event in GS between seasons 2005/2006 and 2019/2020 ($n = 15$ seasons), with a total number of starts for women $n = 3{,}129$ and men $n = 3{,}164$. Based upon the final race results (run 1 + run 2), the number of unique starts for overall race position groups 1–3 (G3), 4–10 (G10), and 11–20 (G20) were in total $n = 2{,}294$ and $n = 2{,}328$ for women and men, respectively. Additionally, the number of starts in the analysis for women and men based on their FIS ranking start/bib groups, 1–7 (B7), 8–15 (B15), and 16–30 (B30) were $n = 2{,}541$ and $n = 2{,}564$, respectively.

Statistical Analysis

Race data were pre-checked for normality using the Shapiro–Wilk test showing that none of the data regarding run time, total time, or gate-to-gate time conformed to normal distribution. Accordingly, a non-parametric Wilcoxon-signed rank test was used for comparisons of the run and average gate-to-gate times between runs 1 and 2 for women and men, separately. The average gate-to-gate time for each run was calculated as the total run time divided by the number of turning gates. A point biserial correlation coefficient (r_{pb}) was used as effect size with small interpretive benchmarks $r_{pb} < 0.10$, medium $r_{pb} > 0.11$ to < 0.36, and large $r_{pb} > 0.37$ (McGrath and Meyer, 2006). Comparisons between the groups as final rank (G3, G10, and G20) and start/bib numbers (B7, B15, and B30) within separate runs using run time and gate-to-gate times were performed using a Kruskal–Wallis test with epsilon squared (ε^2) for determination of the effect size. A Dwass–Steel–Critchlow–Flinger test was applied for pairwise comparisons if there was a global significance for the Kruskal–Wallis test. Furthermore, a multi-nominal logistic regression was used to identify the run times and gate-to-gate times associated between different rank groups (G3, G10, and G20), and an χ^2 test of independence determined the differences between start groups according to BIB number (B7, B15, and B30) and the group rank (G3, G10, and G20) using Cramer's V (V) as the effect size. All statistical analysis was performed using *jamovi* (The jamovi project, 2020). Due to the skewness of the data, the results are presented as a median and interquartile range [IQR], odds ratios (OR) with confidence intervals (95% CI), or with mean values where appropriate. The α level was set to < 0.05.

TABLE 1 | Multi-nominal logistic regression for run times in Giant Slalom FIS World Cup 2005–2020.

Group	OR	95% CI	*p*-value
Women			
G10–G3			
Run 1 (s)	1.066	1.022–1.110	=0.003
Run 2 (s)	0.952	0.915–0.991	=0.015
G20–G3			
Run 1 (s)	1.115	1.071–1.160	<0.001
Run 2 (s)	0.923	0.889–0.959	<0.001
Men			
G10–G3			
Run 1 (s)	1.060	1.019–1.102	=0.004
Run 2 (s)	0.957	0.922–0.994	=0.023
G20–G3			
Run 1 (s)	1.104	1.064–1.147	<0.001
Run 2 (s)	0.932	0.899–0.966	<0.001

Run times (s) represent finishing time for each separate run; G3, place 1–3; G10 place 4–10; G20 place 11–20. Data are reported as odds ratio (OR) with a 95% confidence interval (95% CI) an p-values. An OR > 1.0 along with the 95% CI above 1.0 indicate that the reference group (G3) is faster than G10 and G20. Conversely, if OR is <1.0 with a 95% CI below 1.0 suggest that G3 is slower compared to the other groups, i.e., G10 and G20.

RESULTS

Run Time

Total

The women had similar run times for runs 1 and 2 (69.7 s [64.1–73.7] vs. 69.4 s [64.3–74.1], $z = 2.33$, $p = 0.734$, $r_{pb} = 0.007$), while the men decreased the run time in run 2 (75.0 s [70.8–78.7] vs. 73.9 s [70.5–78.0], $z = 9.44$, $p < 0.001$, $r_{pb} = 0.249$). For the final ranking, the likelihood of being placed in the top group G3 had the strongest association with a fast run 1 for both women and men (**Table 1**). In run 2, the relation was reversed with a faster run most likely in the G20 group (**Table 1**).

Run 1

There was an overall difference between ranked groups for the women's run times in run 1 [$\chi^2_{(2)} = 17.50$, $p < 0.001$, $\varepsilon^2 = 0.00763$]. The G3 group was faster than G20 (68.6 s [63.0–72.2] vs. 69.9 s [64.4–74.1], $p < 0.001$), and G10 was faster than G20 (69.3 s [63.6–73.2] vs. 69.9 s [64.4–74.1], $p = 0.032$). In run 1, for the men, there was an overall difference between groups [$\chi^2_{(2)} = 23.75$, $p < 0.001$, $\varepsilon^2 = 0.01021$] with G3 significantly faster than G20 (73.6 s [69.0–77.1] vs. 75.1 s [71.0–78.9], $p < 0.001$) and G10 faster than G20 (74.4 s [70.0–78.0] vs. 75.1 s [71.0–78.9], $p = 0.009$).

Run 2

No differences were found between the groups in run time for the second run for women [$\chi^2_{(2)} = 3.07$, $p < 0.216$, $\varepsilon^2 = 0.00134$] or men [$\chi^2_{(2)} = 3.06$, $p = 0.216$, $\varepsilon^2 = 0.00132$].

Gate-to-Gate Time

The median number of turning gates was 50 [48–53] and 44 [42–48] for men and women, respectively. No significant difference regarding the number of turning gates between run 1 and run 2 was found for men or women.

Total

The women had similar median gate-to-gate times for runs 1 and 2 (1.54 s [1.49–1.60] vs. 1.55 s [1.50–1.59], $z = -1.94$, $p = 0.560$, $r_{pb} = 0.012$), while the men decreased their median gate-to-gate times in run 2 (1.49 s [1.44–1.56] vs. 1.48 s [1.44–1.53], $z = 4.88$, $p < 0.001$, $r_{pb} = 0.157$).

Run 1

For women, there was a difference in gate-to-gate times in run 1 for the ranked groups [$\chi^2_{(2)} = 66$, $p < 0.001$, $\varepsilon^2 = 0.029$] with G3 having the shortest time compared to both G10 and G20 (1.50 s [1.46–1.57] vs. 1.53 s [1.48–1.59] and 1.54 s [1.50–1.60], both $p < 0.001$) and G10 having a shorter gate-to-gate time than G20 ($p < 0.001$). There was also an overall difference between groups in gate-to-gate time for men in run 1 [$\chi^2_{(2)} = 52.7$, $p < 0.001$, $\varepsilon^2 = 0.023$], with G3 displaying a shorter time than both G10 and G20 (1.46 s [1.42–1.53] vs. 1.48 s [1.43–1.55] and 1.49 s [1.45–1.56], both $p < 0.001$). G10 also had a shorter gate-to-gate time than G20 ($p < 0.001$).

Run 2

In the women's second run there was an overall difference in gate-to-gate times for the ranked groups [$\chi^2_{(2)} = 10.9$, $p = 0.004$, $\varepsilon^2 = 0.00475$]. The only pairwise difference was between G3 and G20 (1.53 s [1.49–1.58] vs 1.54 s [1.50–1.60], $p = 0.006$). For men, there was a difference in gate-to-gate times [$\chi^2_{(2)} = 7.93$, $p = 0.019$, $\varepsilon^2 = 0.00341$], with G3 showing a shorter time compared to G10 (1.47 s [1.43–1.52] vs 1.48 s [1.44–1.53], $p = 0.022$).

Overall, a short gate-to-gate time in the first run was strongly associated with a final rank in G3 (**Table 2**). Although a shorter gate-to-gate time in run 2 showed a greater likelihood to be linked to G20 (**Table 2**), this association was not as strong compared to run 1 in relation to G3.

TABLE 2 | Multi-nominal logistic regression for gate-to-gate times in Giant Slalom FIS World Cup 2005–2020.

Group	OR	95% CI	*p* - value
Women			
G10–G3			
Gate-to-gate run 1 (s)	80.77	9.363–696.9	<0.001
Gate-to-gate run 2 (s)	0.272	0.033–2.189	=0.221
G20–G3			
Gate-to-gate run 1 (s)	2,301	288–18,371	<0.001
Gate-to-gate run 2 (s)	0.115	0.015–0.861	=0.035
Men			
G10–G3			
Gate-to-gate run 1 (s)	33.08	4.229–258.7	<0.001
Gate-to-gate run 2 (s)	0.285	0.922–0.994	=0.281
G20–G3			
Gate-to-gate run 1 (s)	474.6	65.36–3,446	<0.001
Gate-to-gate run 2 (s)	0.085	0.001–0.759	=0.027

Gate to gate times (s) represent finishing time for each separate run; G3, place 1–3; G10 place 4–10; G20 place 11–20. Data are reported as odds ratio (OR) with a 95% confidence interval (95% CI) an p-values. An OR > 1.0 along with the 95% CI above 1.0 indicate that the reference group (G3) is faster than G10 and G20. Conversely, if OR is <1.0 with a 95% CI below 1.0 suggest that G3 is slower compared to the other groups, i.e., G10 and G20.

TABLE 3 | Number of placings for different starting groups in women's FIS World Cup Giant Slalom 2005–2020.

	BIB Group			
Rank Group	**B7**	**B15**	**B30**	
G3 (*n*)	261	65	22	348
G10 (*n*)	261	279	222	762
G20 (*n*)	133	273	500	906
Total (*n*)	655	617	744	2,016
[$\chi^2_{(4,\ N=2{,}016)} = 491$, $p < 0.001$, $V = 0.349$]				

BIB group 7, BIB 1–7; BIB group 15, BIB 8–15; BIB group 30, BIB 16–30; G3, rank 1–3; G10 rank 4–10; G20 rank 11–20.

BIB Group

For both women and men, the B7 group showed the greatest number of placing in G3, while the B30 showed the least numbers (**Tables 3**, **4**, respectively).

There was an overall difference in run time between different BIB groups for the women [$\chi^2_{(2)} = 12.0$, $p = 0.002$, $\varepsilon^2 = 0.00472$], with B7 faster than both B15 and B30 ($p = 0.020$ and $p = 0.003$) and with no differences between B15 and B30 ($p = 0.878$). In run 2, for the women, there was no difference between the BIB groups in the run time [$\chi^2_{(2)} = 2.28$, $p = 0.320$, $\varepsilon^2 < 0.0001$). Within the women's BIB groups, there was a change in ranking between runs 1 and 2 among all groups [$\chi^2_{(2)} = 272$, $p < 0.001$, $\varepsilon^2 = 0.107$]. Two groups lost in ranking with the BIB 7 losing most places −5 (IQR = −12 to 0) and BIB 15 dropping by −3 (IQR −10 to 3), respectively. The only women's group that gained in ranking from the 1 to 2 run was BIB 30 with 2 (IQR = −4 to 9).

TABLE 4 | Number of placings for different starting groups in men's FIS World Cup Giant Slalom 2005–2020.

	BIB Group			
Rank Group	**B7**	**B15**	**B30**	
G3 (*n*)	257	61	26	344
G10 (*n*)	279	276	200	755
G20 (*n*)	134	290	525	949
Total (*n*)	670	627	751	2,048
[$\chi^2_{(4,N=2,048)} = 508$, $p < 0.001$, $V = 0.352$]				

BIB group 7, BIB 1–7; BIB group 15, BIB 8–15; BIB group 30, BIB 16–30; G3, rank 1–3; G10 rank 4–10; G20 rank 11–20.

In the men's race, an overall difference was shown between different BIB groups [$\chi^2_{(2)} = 19.78$, $p < 0.001$, $\varepsilon^2 = 0.00772$], with B7 being faster than both B15 and B30 ($p = 0.011$ and $p < 0.001$). No differences between B15 and B30 were shown ($p = 0.368$). In run 2, there was no effect found in the BIB group on run time for the men [$\chi^2_{(2)} = 1.52$, $p = 0.467$, $\varepsilon^2 < 0.0001$). The change in ranking between the runs 1 and 2 differed within the men's BIB groups [$\chi^2_{(2)} = 344$, $p < 0.001$, $\varepsilon^2 = 0.134$]. Two groups lost in ranking were BIB 7 losing most in ranking −7 (IQR = −15 to −1) and BIB 15 with a drop by −4 (IQR −11 to 4), respectively. The only group that gained in ranking was BIB 30 with 2 (IQR = −4 to 10).

DISCUSSION

This is the first study to report the importance of a fast first run and its strong association with the final ranking in GS events. The first run was found to be equally as important for a final rank for both women and men. Even though a fast second run was most likely to be associated with a lower-ranked group, it did not have the same impact on the final ranking as the first run. The gate-to-gate time and run time remained unchanged between the first and second runs for the women but decreased for the men, potentially showing a need for faster tempo in the second run in general. In addition, a lower BIB number showed greater occurrence in a higher ranking, for both women and men.

Run Time

Previous research on performance profiling in GS has mainly focused on biomechanical aspects using a limited number of skiers ($n < 15$) (Lešnik et al., 2013). As the first study to include data from both sexes spanning over several seasons, the current results demonstrate how critical a fast first run is for final ranking in both women and men. The association between a fast first run was evident to be placed in G3 compared with the other two other groups. Furthermore, these results suggest that it is difficult to change group rankings after run 1. In a previous study (Supej and Cernigoj, 2006a), looking at performance within one specific race during two seasons using a small sample size ($n = 6$), the main outcome was to focus first on technical rather than the tactical aspects. Interestingly, while mainly studying run 1, the authors pointed out that the four fastest skiing times in run 2 were from skiers placed outside the top 20 in the first run. The reversed starting order in run 2 provides the slower skiers the opportunity to ski on a freshly prepared slope. However, as identified by the current study, the reversed starting order in run 2 does not appear as favorable as the skiers do not make up for the time lost in run 1 to climb to a better-ranked group in the final race result. It can be argued that the slower skiers from run 1 are less skilled and lower-ranked, which might explain why the early starting skiers in run 2 cannot make up the time lost from run 1. However, even highly ranked skiers in B7 and B15 who skied poorly in run 1 and started early in run 2, cannot benefit enough from the fresh conditions to make up for the time lost in run 1. Still, there are normally several skiers who improve their ranking between run 1 and run 2, but for top-ranked skiers, the current results show the importance of performing a fast run 1 and that it is unlikely to make up for lost time from the first run by skiing fast in run 2. Hence, even top-ranked skiers are unlikely to move to a better-ranked group, e.g., from G20 in run 1 to G3 in final race results, by skiing fast in run 2.

Gate-to-Gate Time

Both women and men showed faster gate-to-gate times for G3 compared to G10 and G20 in run 1 and run 2, even though there is no difference in the number of turning gates between run 1 and run 2. It can therefore be argued that the reversed staring order in run 2 evens out the advantage by starting early in run 1. Still, the B7 group for men and women has the highest occurrence of G3, which suggests that the skiers in B7 have better skills compared to B15 and B30. However, it is difficult to explain why skiers in, e.g., B7 who finish in G20 after run 1 cannot make up for enough lost time to finish in G10 or G3 overall by performing a fast run 2. In theory, this should be possible, but it would require that they ski poorly enough in run 1 to start among the first seven in run 2, which rarely happens. Also, even though run 2 is a newly prepared course, tracks from run 1 exist on the slope, which means that the fresh conditions in run 2 are not as beneficial as in run 1. It can also be hypothesized that skiers might perform slightly better in run 2 as they are familiar with the snow and conditions from run 1. This could increase the skiers' individual velocity barriers, which would allow them to ski faster without making mistakes (Supej et al., 2011; Gilgien et al., 2020; Cross et al., 2021). Speculatively, B7 skiers might be better at benefiting from this phenomenon compared to B15 and B30 skiers. However, this is yet to be investigated.

BIB Group

The frequency of numbers of skiers in the G3 group was evident for the skiers in the first BIB group (B7). Moreover, it was as common to end up in G3 and G10 for both women and men starting in B7 for run 1. While the B15 group that started between 8 and 15th place finished mostly in G10 and G20, indicating the importance of the start order, which provides the skiers with better snow conditions for optimal performance. This result is in accordance with previous results by Lešnik et al. (2013), despite them only investigating the first 15 skiers in run 1 during one European Cup slalom race. Still, the skiers in B7 are the seven best-ranked and are hence most likely to ski the fastest in run 1.

However, run 2 has a reversed starting order, meaning that the fastest skiers in run 1 are starting last in the run 2. This gives the slower skiers from run 1 the opportunity to ski on a freshly prepared slope in run 2 and hence the best conditions to make up the lost time from run 1. Nevertheless, the slowest skiers from run 1 who qualified for run 2 still most often ended up in the lowest-ranked group, G20, with a ranking between 11 and 20, and the starting order did therefore not directly impact their final standings; there are other contributing factors. This suggests that the group that starts late in run 1 is not at an equal performance level as the skiers starting before them as these skiers still cannot make up time lost in during run 2 even after being provided optimal snow conditions. However, skiers obviously gain positions in run 2 also, but the present results show that these gained positions most often are within the group in which they started the run 2. Hence, it is unlikely for both men and women to gain enough positions to change the final position group compared to the position group after run 1, especially for B7 performing a poor run 1 and starting early in run 2.

Comparison Between Women and Men

For the men, run 2 compared to run 1 has shorter run times with shorter gate-to-gate times. This is not the case for the women who have similar run times and gate-to-gate times in the first and second run. The reason for the faster pace of the men could be due to straighter courses with less traversing. In GS, Alejo et al. (2021) showed that male skiers benefit from skiing on a longer trajectory which allows them to maintain higher skiing speeds. However, female skiers do not seem to be able to maintain high enough skiing speeds when skiing on longer trajectories, which results in a worse ranking (Alejo et al., 2021). To avoid the tracks from run 1, it is likely that skiers are forced to use a longer skiing trajectory at different places in run 2. Compared to women, male skiers seem to be better at maintaining higher skiing speeds with longer trajectories which, together with an increase's velocity barrier, might explain why male skiers have a faster run 2 compared to run 1.

CONCLUSION

This is the first study to report that the final group rank in GS is strongly related to a fast run 1. Even though run 2 favors the slower skiers from run 1, the favorable conditions in run 2 are not enough to reverse the final group rank. Lower start numbers and hence an early start order in run 1 seem favorable for the final ranking group. In the men's race, the faster gate-to-gate times in run 2 stress the importance of the ability to ski with a faster tempo to be in contention for a better final rank.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://www.fis-ski.com/en/alpine-skiing.

AUTHOR CONTRIBUTIONS

GB and MS designed the study, performed the data analysis, interpreted the results, wrote the manuscript, revised the manuscript, approved the final version, and agreed to be accountable for all aspects of the study. All authors contributed to the article and approved the submitted version.

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A screening instrument for side dominance in competitive adolescent alpine skiers

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Previous research has shown that high school ski students injure their left anterior cruciate ligament (ACL) more often than their right ACL, and that a prevention program focusing on equal load to the right and left ski turns prevents ACL injuries. Whether the injuries were in the dominant or non-dominant side of ski students was not determined but may be important knowledge to ski coaches for future design of ski-specific training programs. There is no gold standard on how to investigate the dominant side of alpine skiers. Therefore, the aim of this study was to develop a screening instrument consisting of five questions for identifying side dominance and to evaluate side dominance in competitive adolescent alpine skiers. First, 121 competitive adolescent alpine skiers answered the questions on side dominance using a test-retest design. The questions were: which hand/arm (left/right) or foot/leg (left/right) one uses as the first choice when writing, throwing, kicking a ball, jumping over a fence and stair-climbing. A question about safer/better ski turn to the left or to the right was also added. Second, 274 skiers answered the questions at one occasion. A very good agreement was shown in writing and throwing and kicking a ball, and a fair agreement was shown in jumping over a fence and stair climbing. A total of 243 skiers reported right-sided dominance, and seven skiers reported left-sided dominance. One hundred and nineteen of the 121 skiers who took part in the test-retest design answered the question safer/better ski turn, and of those 70 (59%) reported that they had a safer/better ski turn to one side than to the other side. However, the side was not consistent between the two test occasions, and the question did not correlate with side dominance. A combination of the three questions "What hand/arm do you use as first choice when writing?" "What hand/arm do you use as first choice when throwing?" and "What foot/leg do you use as first choice when kicking a ball?", may be used to decide side dominance in adolescent alpine skiers. Most adolescent alpine skiers reported right-sided dominance.

KEYWORDS

alpine skiers, ACL injury, adolescent, dominance, footedness, handedness, ski turn

Introduction

Dominant vs. non-dominant side is commonly discussed when it comes to physical performance and injury risk factors in different sports. However, the definition of the dominant and non-dominant sides often varies between studies.

Hewett et al. (1996, 2001) defined leg dominance as a side-to-side difference in muscle strength and coordination, where the dominant leg is superior to the non-dominant leg for both muscle strength and coordination. Herring (1993) defined dominance as the ability of an individual to perform a certain task with greater accuracy, speed, and agility with the dominant leg than with the non-dominant leg. Ross et al. (2004) reported better knee joint proprioception, thigh muscle strength, and knee flexion range of motion of the dominant leg than the non-dominant leg. Moreover, a dominant or non-dominant side is less evident in terms of the lower extremities than the upper extremities, meaning that a side-to-side difference is much more common in the upper extremities than in the lower extremities (Gabbard, 1993). In the general population, the prevalence of right-leg dominance varies between 75 and 93% (Didia and Nyenwe, 1988; Gabbard, 1993; Gabbard and Iteya, 1996; Schneiders et al., 2010; Ziyagil, 2011; Steidl-Müller et al., 2018). The corresponding number for the upper extremities is 89–96% (Chapman and Chapman, 1987; Ziyagil, 2011).

Several studies on the area of sports medicine have defined dominant leg to be the leg that one chooses when kicking a ball (Ross et al., 2004; Negrete et al., 2007; Brophy et al., 2010; Ruedl et al., 2012). The most commonly used tests are kicking a ball, unilateral balance with eyes closed, and hopping. These tests are thought to evaluate both muscle force and joint stability of the lower extremities (Gundersen et al., 1989; Herring, 1993). A side-to-side difference can increase injury risk in either the dominant or the non-dominant leg (Hewett et al., 2010). For example, the individual may rely too much on the dominant leg and thereby injure that leg, or the non-dominant leg may be injured due to decreased muscle strength and impaired coordination (Hewett et al., 2010).

Leg dominance has been discussed as a potential risk factor for sustaining an anterior cruciate ligament (ACL) injury (Matava et al., 2002; Negrete et al., 2007; Brophy et al., 2010; Ruedl et al., 2012). Negrete et al. (2007) studied the relationship among leg dominance, side of injury, and gender on 302 subjects with non-contact ACL injuries. Both genders injured the dominant as well as the non-dominant leg, and men and women did not differ in this aspect. However, they found a strong tendency for the women to injure their left knee compared to their right knee. This was also found by Brophy et al. (2010) who reported that the left knee was injured in 68% of female soccer players and 26% of male soccer players with non-contact ACL injuries. They found that male soccer players more often injured their kicking leg (dominant leg) than their supporting leg (non-dominant leg), whereas female soccer players predominantly injured their supporting leg (non-dominant leg). In another study (Matava et al., 2002), the dominant knee was not found to be a risk factor for sustaining a non-contact ACL injury. However, in a study on 143 German female soccer players the dominant leg was found to be more injury-prone regarding overuse and contact injuries (Faude et al., 2006).

The incidence of injuries in both recreational and competitive alpine skiers is high, and most injuries are related to the lower extremities. Whether the injuries occur in the dominant or non-dominant side is rarely reported. In an epidemiological study during 25 ski seasons, no side differences were found investigating ACL injuries (Pujol et al., 2007). In another study on recreational skiers, it was shown that 63% of ACL injuries were to the left knee (Urabe et al., 2002), and that female alpine skiers had twice as high risk to sustain an ACL injury in their non-dominant leg compared to their dominant leg (Urabe et al., 2002; Ruedl et al., 2012). Westin et al. (2012) showed that it was a higher risk to sustain an ACL injury in the left than in the right knee in adolescent alpine skiers (Westin et al., 2012, 2018). Whether this was in the dominant or non-dominant side was not determined.

Majority of publications in sports medicine define side dominance using only one question (Herring, 1993; Faude et al., 2006; Negrete et al., 2007; Brophy et al., 2010; Ruedl et al., 2012). Side dominance is often used to find out whether a functional movement is performed better on one leg compared to the other. However, functional hop tests are complex and challenge the whole body. Therefore, we find it important to take into account both the lower and upper extremities. Moreover, it is likely to be believed that using only one question may not be sufficient to determine side dominance.

The aim of this investigation was to develop a screening instrument consisting of five questions regarding side dominance in competitive adolescent alpine skiers. The second aim was to conduct a survey identifying side dominance, and the third aim was to study whether competitive adolescent alpine skiers had a safer/better ski turn to the left or to the right and if this was correlated with side dominance.

Methods

Design and ethical approval

A test-retest design to develop a screening instrument for dominance and a cross-sectional design to determine dominance in competitive adolescent alpine skiers were used in 2012. The study was approved by the Swedish Ethical Review Authority (Dnr 2006/833-31/1). Oral and written consent was collected from all participating skiers.

TABLE 1 Kappa coefficient, which is the quantity of agreement, adjusted for chance, and percentage of agreement between the first and second test occasions.

Task	Answers				Kappa analysis	
	(n)	Left (n)	Right (n)	Ambivalent (n)	Agreement (%)	Kappa coefficient
Writing	121	5	116	0	100	1.0
Throwing	121	3	118	0	100	1.0
Kicking	118	6	112	0	100	1.0
Jumping	119	19	71	19	75.6	0.4
Climbing	114	10	73	31	72.8	0.22

Subjects

All competitive adolescent alpine skiers studying in one of the Swedish ski high schools during the spring and/or the autumn 2012 were asked to participate in the study. In the first test occasion (spring 2012), 252 skiers were invited, and 198 accepted the invitation. In the second test occasion (autumn 2012), 241 skiers were invited and 197 accepted the invitation.

A total of 274 competitive adolescent alpine skiers (130 men, mean age 17.8 ± 1.3 years, and 144 women, mean age 17.7 ± 1.4 years) accepted to participate in the study. Of these, 121 competitive alpine skiers (59 men/62 women) were included in a test-retest design and answered the screening instrument in two occasions with approximately 4 months in-between the tests.

Screening instrument

The screening instrument consisted of five questions about side dominance and was obtained from earlier publications (Chapman and Chapman, 1987; Chapman et al., 1987; Didia and Nyenwe, 1988; Elias et al., 1998; Annett, 2000). Two questions focused on the upper extremities: "which hand do you prefer to write with (writing) and which arm do you prefer to throw with (throwing)?", while three questions focused on the lower extremities: "which foot do you prefer to kick a ball with (kicking), which leg do you prefer to lift first when jumping over a fence (jumping), and which leg do you prefer to lift first when climbing a stair (climbing)?". In addition, there was a sport-specific question: "do you have a safer/better ski turn to the left or to the right?".

Procedure

Each skier answered the questions under the supervision of the principle investigator (MW). Skiers who were uncertain about how to answer were allowed to practice the tasks before giving the answer.

Statistical analyses

Descriptive data are presented with mean ± SD and frequencies and percentages. Cohen's kappa analysis was conducted to assess the test-retest reliability of the questions. The results were interpreted according to the recommendation by Landis and Koch (1977) (0.01–0.2 poor agreement, 0.21–0.4 fair agreement, 0.41–0.6 moderate agreement, 0.61–0.8 substantial agreement, and 0.81–1 almost perfect/excellent). Percentage agreement was also calculated to evaluate the agreement between the two test occasions. An explorative factor analysis was completed to explain the variability between the sets of tasks. In cases where a skier had not answered a question, the question was excluded as missing, while the other questions were included in the survey of dominance. Chi-2 square test was conducted to evaluate differences between male and female skiers. Level of statistical significance was set at $p < 0.05$. All statistical tests were processed using STATISTICA 10.0.

Results

Test-retest reliability

A total of 121 subjects participated in the test-retest of the questions. The results of the test-retest showed a kappa of 1 for the three questions about writing, throwing, and kicking a ball. The questions about jumping over a fence and stair climbing showed a kappa of 0.4 and 0.22, respectively (Table 1).

The exploratory factor analysis demonstrated that writing, throwing, kicking a ball, jumping over a fence, and stair-climbing were loaded on two factors in both test occasions. In the first test occasion, the two factors explained 54% of the variance and in the second test occasion 57%. Writing throwing, and kicking a ball were loaded to one factor, and jumping over a fence and stair-climbing were loaded to another factor. The question about safer/better ski turn did not show any relationship to the other five questions (Table 2).

Survey of side dominance

The questions about jumping over a fence and stair-climbing showed a fair agreement and were therefore excluded from the survey. Consequently, side dominance was defined when the skier gave the same answer, left or right, on the following three questions about writing, throwing, and kicking a ball.

Out of the 274 skiers, 243 reported right-sided dominance regarding the questions writing, throwing, and kicking a ball, while seven reported left-sided dominance (Table 3). In total, 253 of the skiers (92%) preferred to use the right hand when writing, 260 (96%) preferred to throw with the right arm, and 253 (94%) chose the right leg for kicking a ball (Table 3). The female skiers showed a higher percentage of matched answers than the male skiers (Table 3). The female skiers were, to a greater extent, right-dominant regarding each separate question (Table 3).

Ski turn

One hundred and nineteen of skiers answered the question about safer/better ski turn twice. Out of these, 70 answered a safer/better ski turn in one direction, 27 answered that they did not have a safer/better ski turn, and 22 reported different answers in the first and second test occasions. A total of 97 matched answers (kappa 0.58) were judged to be a moderate agreement. Of the 70 skiers that reported to have a safer/better ski turn, 47 answered the same direction in both test occasions, 30 answered the left turn, 17 the right turn, and 20 were uncertain. Three skiers did not answer direction (left/right) the second time and thus were treated as dropouts. No gender differences were shown regarding the answers about ski turn.

Sixteen out of the 17 skiers who answered a safer/better ski turn to the right in both test occasions were also categorized as right-side dominant, meaning they preferred to write with the right hand, throw with the right arm, and kick a ball with the right foot (kappa 1). One skier preferred to use the left hand when writing, throwing, and kicking a ball. Twenty-seven out of the 30 skiers who answered a better/ safer ski turn to the left reported right-sided dominance, and three answered the right side in two of the three questions. No kappa analysis could be conducted because of the absence of left-side dominance. Eighteen out of the 20 skiers who were uncertain reported right-side dominance and one left-side dominance (kappa 0.95). One skier answered right side in two of the three questions.

Seventy out of the 153 skiers who only answered the question once reported a safer/better ski turn to the left, 54 to the right, and 28 did not report to have any safer/better direction of their ski turn.

TABLE 2 Exploratory factor analysis on the first and second test occasions.

Task	Test occasion 1				Test occasion 2			
	Factor 1		Factor 2		Factor 1		Factor 2	
Writing	0.82*			0.07	0.86*			0.04
Throwing	0.87*			0.05	0.87*			0.18
Kicking	0.80*			0.01	0.73*			−0.09
Jumping		0.12	0.69*			0.14	0.81*	
Climbing		0.02	0.75*			0.00	0.83*	
Ski turn		0.01	−0.38			0.02	−0.10	

*$p < 0.05$.

Discussion

The overall aim of the present investigation was to develop a screening instrument for identification of dominant/nondominant side in adolescent competitive alpine skiers. The tasks writing, throwing, and kicking a ball showed an almost perfect agreement, while the tasks jumping over a fence and climbing a stair showed a fair agreement. Despite the moderate agreement demonstrated in the questions about jumping over a fence and the foot one prefers to use when climbing a stair, the kappa coefficient was low. This can be explained by the fact that the kappa coefficient is high if the outcomes of various alternatives are approximately equal (Feinstein and Cicchetti, 1990). The female skiers reported a higher number of matched answers than the male skiers, which is in accordance with the previous research by Schneiders et al. (2010). The second aim of this study was to determine whether the skiers were right- or left-side dominant. In the survey, the

TABLE 3 Distribution of the answers about dominant/non-dominant side for each question.

Task	Male skiers ($n = 130$)			Female skiers ($n = 144$)			All skiers ($n = 274$)		
	Left *n* (%)	Right *n* (%)	Drop-out (*n*)	Left *n* (%)	Right *n* (%)	Drop-out (*n*)	Left *n* (%)	Right *n* (%)	Drop-out (*n*)
Writing	14 (11)	116 (89)	0	7 (5)	135 (95)	0	21 (8)	253 (92)	0
Throwing	9 (7)	121 (93)	0	3 (2)	139 (98)	2	12 (4)	260 (96)	2
Kicking a ball	10 (8)	117 (92)	3	7 (5)	136 (95)	1	17 (6)	253 (94)	4

tasks jumping over a fence and climbing a stair were excluded because of low kappa values in the reliability study. The result of the survey showed that majority of the skiers reported the right side to be the dominant side (89%). This is in line with the general population (Didia and Nyenwe, 1988; Gabbard, 1993; Gabbard and Iteya, 1996; Schneiders et al., 2010; Ziyagil, 2011) and higher than previously published when using several questions (Chapman and Chapman, 1987; Chapman et al., 1987; Didia and Nyenwe, 1988; Friberg and Kvist, 1988; Gabbard, 1993; Gabbard and Iteya, 1996) or solely one question (Brophy et al., 2010; Ruedl et al., 2012).

In the literature there are a number of quantitative assessment scores reporting good reliability in terms of side dominance of the arm/hand such as the Edinburgh Handedness Inventory (Oldfield, 1971) and Chapman and Chapman (1987) measurement of handedness. Both these scores include a large number of tasks that may jeopardize the compliance in answering the questions. Therefore, we chose solely five questions in order to assess side dominance. In accordance with the Edinburgh Handedness Inventory (Oldfield, 1971) and the measurement of handedness by Chapman and Chapman (1987), our survey included the tasks writing and throwing. A recent publication with a short form of the Edinburgh Handedness Inventory including these questions was found to have a good reliability (Veale, 2014). Schneiders et al. (2010) conducted a reliability study that included 12 different lower limb performance tasks and found that kicking a ball had a substantial agreement, and that climbing a stair had a fair agreement (Schneiders et al., 2010). They also found that self-rated side dominance of the lower extremities was only correlated with the tasks kicking a ball and picking up a marble (Schneiders et al., 2010).

In the present study the factor analysis showed that writing, throwing and kicking a ball were loaded to one factor and the question jumping over a fence and climbing a stair were loaded to another factor. Schneiders et al. (2010) also found that kicking a ball and stair-climbing were loaded to different factors. One might speculate that kicking and throwing a ball are something that a child starts with quiet early in life and therefore is not influenced by the surrounding environment when choosing which hand or foot to use. We know that the cerebral hemispheres are asymmetric (Steinmetz, 1996), and that individuals almost always choose one side over the other (Gabbard, 1993; Gabbard and Iteya, 1996). However, previous literature has shown that children in general are two-footed until around the age of 11 years old and thereafter become more or less lateralized (Gabbard and Iteya, 1996). Consequently, a more complex skill such as alpine skiing may be influenced by side preferences but possibly also how skills are learned and thus not necessarily guide us to understand laterality.

In a study on competitive alpine skiers, Westin et al. (2012) reported that two-thirds of lower extremity injuries occurred in the left leg. Based on this information, the question on safer/better ski turn was formulated. All the skiers, except for one who reported to have a safer/better ski turn, were classified as right-side dominant according to our three questions, although no correlation between side dominance and ski turn was found. Twenty percent of the skiers in the test-retest were sure of having a safer/better ski turn but were unsure of what direction, left or right. A possible reason for this uncertainty could be the time of the test occasions, in the beginning and at the end of the preseason, when the skiers had not yet been on snow. Another reason may be that the direction of a safer/ better ski may be more of a learned skill than a native skill. Whether knowledge of side dominance is helpful in understanding the direction of a safer/better ski turn is not known and can be questioned if the ski turn is altered between test occasions. However, since skiing is an equilateral sport, awareness of dominance may be helpful knowledge in the training phase of alpine skiing. According to Hewett et al. (2010), the non-dominant side lacks strength and coordination compared to the dominant side and thereby possibly needs more attention. When implementing a prevention program focusing on the skier's ability to perform neuromuscular exercises equally good on both legs, it could be helpful for the skier to understand where his or her weaknesses lie. To highlight dominance may therefore be of further help during training to become equally good in both directions in alpine skiing.

This study included a homogenous group of adolescent competitive alpine skiers and can therefore only be generalized to young alpine skiers. The same investigator supervised both test occasions ensuring the same instructions was given, which could be regarded as a study strength. The time of 4 months between the two test occasions may reduce possible recall bias, although side dominance is suggested to be stable after the age of 11 years (Gabbard and Iteya, 1996).

Conclusion

The reliability test of side dominance showed an almost perfect agreement in the tasks writing, throwing, and kicking a ball. Using three questions, the alpine ski students reported right-side dominance. There was a considerable uncertainty among the alpine skiers whether they had a safer/better ski turn to the left or to the right, and this was not correlated with side dominance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MW and SW have given substantial contribution to the conception and design of the study. Acquisition of data by AN, and analysis and interpretation by MW, AN, MH, and SW. The manuscript was drafted by MW. All authors critically revised, read, and approved the final version of the manuscript.

Conflict of interest

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.

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Repeated practice runs during on-snow training do not generate any measurable neuromuscular alterations in elite alpine skiers

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Background: Alpine skiers typically train using repeated practice runs requiring high bursts of muscle activity but there is little field-based evidence characterizing neuromuscular function across successive runs.

Purpose: To examine the impact of repeated ski runs on electromyographic activity (EMG) of the knee extensors and flexors in elite alpine skiers.

Methods: Nineteen national team alpine skiers were tested during regular ski training [Slalom (SL), Giant Slalom (GS), Super Giant Slalom and Downhill (Speed)] for a total of 39 training sessions. The surface EMG of the *vastus lateralis* (VL), *rectus femoris* (RF), *vastus medialis* (VM), *biceps femoris* (BF) and *semimembranosus/semitendinosus* (SMST) muscles was continuously recorded along with right knee and hip angles. The EMG *root mean square* signal was normalized to a maximal voluntary contraction (%MVC). The first and fourth runs of the training session were compared.

Results: There was no meaningful main effect of run on EMG relative activation time or mean power frequency beyond the skier's intrinsic variability. However, EMG activity of the *vastii* increased from the first to the fourth run in SL [VM, ∼+3%MVC for IL and outside leg (OL), $p = 0.035$)], speed (VL, IL:+6%/OL:+11%, $p = 0.015$), and GS (VM, IL:0/OL:+7%, $p < 0.001$); the later with an interaction with leg ($p < 0.001$) due to a localized increase on the OL. The run time and turn time did not change from the first to the fourth run. There were no meaningful changes in angular velocities, amplitude of movement, or maximal and minimal angles.

Conclusion: Neuromuscular activity remains highly stable in elite skiers with low variability across four runs.

KEYWORDS

winter sport, surface electromyogram, injury prevention, muscle fatigue, alpine ski, elite athlete, variability

Introduction

Alpine ski racers face multiple constraints during racing, such as event-specific gate setups and variable terrain conditions that require well-developed skiing skills and physical abilities (White and Johnson, 1993). Course performance (run time) in alpine skiing is multifactorial including tactical (Federolf, 2012; Cross et al., 2021a), biomechanical (Meyer, 2012; Hébert-Losier et al., 2014), kinetic/kinematic (Supej and Holmberg, 2019), and neuromuscular requirements (Berg et al., 1995; Hintermeister et al., 1995; Berg and Eiken, 1999; Turnbull et al., 2009). Alpine skiing requires high eccentric and quasi-static loads on the knee extensors to sustain very large radial forces during the turns (Berg and Eiken, 1999; Kröll et al., 2015b; Alhammoud et al., 2020). Therefore, it is established that elite skiers must generate high leg force levels (Berg et al., 1995; Hintermeister et al., 1995; Kröll et al., 2015a,b; Steidl-Müller et al., 2018) to control their speed appropriately when they are close to their "velocity barrier," above which they make trajectory mistakes (Supej et al., 2011). Alpine skiing is described as a symmetrical sport due to repeated bidirectional turns (Turnbull et al., 2009). However, the load distribution of lateral forces is about 80% on the outside ski from 50 to 70% of the turn in GS. This is due to a progressive increase of the forces on the outside leg (OL) while the load on the inside leg (IL) remains constant (Meyer et al., 2019). Force measurements have been used to gain insight into the skier's technique such as load evolution during turns and force distribution between leg sides (Meyer et al., 2019). A higher radial force production was explained by a greater capability of the lower limbs to produce total force whereby a greater proportion of this force was applied radially (i.e., in an efficient manner). The skiers with superior physical and technical abilities also select strategies that enable them to minimize dissipation of energy regardless of the trajectory (Meyer and Borrani, 2018; Cross et al., 2021a). An efficient skiing technique requires a well-developed technical ability to apply force onto the snow. It is therefore worthwhile to study the underpinning neuromuscular aspects of the force output in skiers, for each body side independently. Surface electromyogram (EMG) is a useful non-invasive tool to describe the on-snow neuromuscular strategy employed by skiers, which has received little attention so far at elite level (Berg et al., 1995; Hintermeister et al., 1995; Berg and Eiken, 1999; Raschner et al., 2001; Kröll et al., 2005a).

A competitive alpine ski run typically lasts ∼45 s to ∼2 min (White and Wells, 2015; Stöggl et al., 2018). Importantly, ski runs are repeated several times at near-maximal intensity (Zeglinksi et al., 1998) with the primary goal of on-field training to improve the skier's technique. The literature on the neuromuscular adaptations occurring with the repetition of run in elite skiers is limited and showed either neuromuscular alterations post-skiing or an increase in completion time and rate of incomplete runs while skiing in SL and GS (Tomazin et al., 2008; White and Wells, 2015). Force application remains reproducible on-snow in elite skiers following similar trajectory at the same velocity through imposed gates with very stable performance (Meyer et al., 2019; Cross et al., 2021b). However, available surface EMG literature have mainly focused on fatigue manifestation in recreational to experienced skiers (Casale et al., 2003; Kröll et al., 2005b, 2011; Ushiyama et al., 2005; Akutsu et al., 2008; Kiryu et al., 2011), questioning relevance of these findings to elite competitors.

Consequently, the aim of this pilot study was to characterize on-field neuromuscular adjustments and EMG variability in elite skiers repeating four high-intensity runs. Our real-world approach involved comparing knee extensors/flexors muscle activity patterns with bilateral leg comparison across three disciplines. We hypothesized that repeating high-intensity runs would induce minimal modifications in the EMG intensity of the thigh muscles, yet without alterations of the athlete's skiing technique and performance.

Materials and methods

Participants

Nineteen French national team alpine skiers participated in this study [8 females (23 ± 2 years, 169 ± 5 cm, and 65.0 ± 4.3 kg) and 11 males (24 ± 5 years, 178 ± 7 cm, and 76.2 ± 7.0 kg)]. The International Ski Federation (FIS) points (the lower the better) were on average 11 ± 6 (Europa Cup n = 7; World Cup n = 12). The participants followed their regular ski training program, performing in one or several disciplines, with a maximum of two athletes tested per day (Table 1). A total of 39 "training sessions x skier" (triplet with the day of test, skier, and discipline) were recorded, including 12 skier-sessions in SL, 19 in GS, and 8 in Speed regrouping Super Giant Slalom (SG) and Downhill (DH). The participants were provided with medical clearance to compete. A power analysis with a power of 0.80, a type 1 error at 0.05 and an expected effect size of

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Abbreviations: AccR, resultant acceleration; BF, *biceps femoris*; CV_{intra}, intra skier-session coefficient of variation; CV_{random}: coefficient of variation due to the random effect between skier-sessions; CV_{syst}, systematic coefficient of variation due to the fixed effects; EMG, surface electromyographic signal; ES, effect size; FIS, International Ski Federation; GS, Giant Slalom; ICC_{adj}, adjusted intraclass correlation coefficient; ICC_{cond}, conditional intraclass correlation coefficient; ID, skier-session; IL, inside leg; MPF, mean power frequency; MVC, maximal voluntary contraction; OL, outside leg; R^2c, conditional R squared; R^2m, marginal R squared; RF, *rectus femoris*; RMS, *root mean square* of the electromyographic signal; SE, Standard Error; SL, Slalom; SMST, *semimembranosus/semitendinosus*; Speed, Super Giant Slalom and Downhill disciplines; VL, *vastus lateralis*; VM, *vastus medialis*.

$f = 0.25$ (moderate) indicated a required sample size of 22 skier-sessions (G*Power v.3.1.9.7). The study was approved by the local university committee of Lyon, with all participants providing written informed consent. All procedures conformed to the standards of the Declaration of Helsinki.

General procedure

The data collection occurred during regular in-field practice (years: 2016–2017; location: Cerro Castor, Ushuaïa, Argentina). Each training session included an average of 6.2 ± 1.3 runs for SL, 5.5 ± 0.5 for GS, and 5.5 ± 0.8 for Speed. For standardization purposes, due to uneven number of runs between the days of testing, runs 1 and 4 were always compared (or runs 2 and 5 in case of an incomplete first or fourth run when the skier did not finish the run). This choice was arbitrary as the competitions consisted of two runs in technical disciplines and one run only in speed disciplines. It was also in the lower range of a training session that generally includes at least 4 runs, and sometimes up to 12 runs in technical disciplines, or 8 runs in speed disciplines. The surface EMG activity of the right leg was synchronously monitored as well as hip and knee angles. The runs were timed and course settings matched the FIS regulation. The visibility was either good (51%, sunny/clear weather) or reduced (49%, snow falling or overcast); the track was smooth (62%) or bumpy (38%); the snow was qualitatively described by the coaches as fresh (49%), changing (41%), artificial (8%) or injected (3%) but mainly hard with regular sleepers between skiers (Table 1). The average run duration was 34.9 ± 8.5 s in SL, 47.8 ± 9.6 s in GS, and 49.0 ± 8.4 s in Speed. All subjects followed a routine indoor warm-up upon arrival in the ski resort followed by ∼45 min to 1 h of free skiing, as reported elsewhere (Alhammoud et al., 2021a) with the rotation time between runs of ∼20 min including ∼9 min of chairlift.

Measurements

Electromyography

Wireless surface EMG electrodes (Trigno, Delsys, Boston, USA) were positioned on the *vastus medialis* (VM), *rectus femoris* (RF), *vastus lateralis* (VL), *biceps femoris* (BF), and *semimembranosus/semitendinosus* (SMST) muscles of the right leg according to the SENIAM recommendations (Hermens et al., 2000). The skin was shaved and cleaned with an alcohol swab before electrodes placement. The data were recorded at 1,926 Hz with a gain of 300 by a portable datalogger (TPM, Delsys, Boston, USA). The raw EMG signal was filtered with a second-order Butterworth bandpass filter (20–500 Hz). Artifacts were automatically removed if the EMG intensity exceeded an upper and lower EMG intensity threshold computed as the *root mean square* (RMS) mean ± 6 × SD. Following this, the cycles containing signals with large artifacts—typically caused by transient and random vibrations inherent to alpine skiing (Supej and Ogrin, 2019)—were visually excluded after inspection. Baseline fluctuation was removed *via* a 1 s moving average. The RMS was calculated over a 125-ms epoch and normalized to an isometric maximal voluntary contraction (MVC). For the normalization of the quadriceps (VL, RF, and VM), the participants performed an isometric knee extension in a sitting position with the knee at 110° and the hip at 90° (180° representing full extension). For the hamstrings (BF and SMST), the participants performed a knee flexion in prone position with the knee at 135° (180° representing full extension). The force was recorded *via* a strain gauge (S-type, Interface, Scottsdale, Arizona, USA) and the maximum RMS activity was defined as the highest 500 ms of the EMG signal during the force plateau. At least three knee extensions and three knee flexions were performed and only trials within 10% of the maximal force recorded during the procedure were averaged as the reference value representing the maximal neural drive obtained during MVC tests.

Performance and goniometry

The performance and kinematic parameters were reported to give a perspective to the potential neuromuscular changes. Indeed, the disciplines of neurophysiology and physics (mechanics) provide a neuromechanical perspective on the study of human movement (Enoka, 2008). The primary macroscopic performance parameter was the run time, measured using an approved FIS wireless system composed of a starting-gate wand and a dual-beam photocell at the final gate of the course. Knee and hip angles of the right leg were monitored through electrogoniometers (SG 150, Biometrics Ltd, Newport, UK) at 148 Hz following the procedures detailed elsewhere (Alhammoud et al., 2020, 2021b). The goniometer had a resolution of +0.1° in a range of 180°, a repeatability of 1° and an accuracy ±2° measured over a range of 90°. Following visual inspection of the amplitude spectral density and Bode plots (Alhammoud et al., 2020), the angles were low-pass filtered (fourth-order Butterworth, cut-off frequencies of 0.5, 1, 2, and 2.5 Hz for DH, SG, GS, and SL, respectively) to remove the higher frequency domain data such as noise and vibrations (Nemec et al., 2001; Spörri et al., 2017). The power spectral density peaks of acceleration at the shank of elite skiers below 4 Hz are most likely related to the frequency of GS/SL turns and/or to the skier's movements (Spörri et al., 2017). The higher frequencies would have likely been dampened by the musculotendinous structures (Mester, 1997) and by the joints (Fasel et al., 2016; Spörri et al., 2017). Indeed, the knee joint attenuates the signal power of nearly all occurring vibrations in both GS and SL for elite skiers, while the hip joint dampens the vibrations particularly at frequencies <10 Hz

TABLE 1 Description of the skier-sessions ($n = 39$).

Triplet			Gates	Alt.	Drop	Incline	Snow			Weather	Visibility	Air temp.
Skier, Date, Discipline			(n)	start	(m)	(%)	Condition	Hardness	Surface			(°C)
S1	13092016	DH	13	872	240	24.7	fresh	hard	smooth	foggy/cloudy	reduced	8.0 (0.0)
S2	22092016	DH	13	872	240	24.7	changing	hard/soft	smooth	foggy/cloudy	reduced	3.7 (0.6)
S3	22092016	DH	13	872	240	24.7	changing	hard/soft	smooth	foggy/cloudy	reduced	3.7 (0.6)
S4	11092016	SG	18	872	240	24.7	fresh	hard	smooth	clear/sunny	good	5.3 (1.2)
S5	11092016	SG	18	872	240	24.7	fresh	hard	smooth	clear/sunny	good	5.3 (1.2)
S2	12092016	SG	18	872	240	24.7	fresh	hard	smooth	clear/sunny	good	3.7 (2.5)
S6	21092016	SG	20	889	240	22.4	changing	hard/soft	bumpy	foggy/cloudy	reduced	10.3 (0.6)
S3	12092016	SG	18	872	240	24.7	fresh	hard	smooth	clear/sunny	good	3.7 (2.5)
S7	01092017	SL	32	532	78	19.9	fresh	hard	smooth	foggy/cloudy	reduced	4.0 (1.0)
S7	21082017	SL	32	308	89	23.4	changing	soft	bumpy	clear/sunny	good	6.3 (1.2)
S8	21082017	SL	32	308	89	23.4	changing	soft	bumpy	clear/sunny	good	6.3 (1.2)
S8	25082017	SL A	46	428	140	29.2	fresh	hard	smooth	snowy	reduced	1.3 (0.5)
S8	25082017	SL B	17	288	66	35	fresh	hard	smooth	snowy	reduced	1.3 (0.5)
S8	31082017	SL	47	669	199	DM	injected	icy	smooth	cloudy	reduced	5.7 (0.6)
S9	09092016	SL A	28	439*	259*	38.9*	artificial	hard/icy	smooth	clear/sunny	good	2.7 (1.2)
S9	09092016	SL B	30				artificial	hard/icy	smooth	clear/sunny	good	2.7 (1.2)
S10	18092016	SL	44	622	132	29.7	changing	hard	smooth	clear/sunny	good	7.3 (1.5)
S11	25092016	SL	45	620	145	30.3	artificial	hard	bumpy	foggy/cloudy	reduced	7.3 (2.3)
S12	17092016	SL	35	464	161	27	changing	hard	bumpy	foggy/cloudy	good	4.3 (1.5)
S13	23092016	SL	45	604	128	29.7	changing	hard/soft	bumpy	foggy/cloudy	good	10.0 (1.0)
S14	01092017	GS	34	461	247	25.4	fresh	hard	smooth	clear/sunny	good	4.0 (1.0)
S7	01092017	GS	34	461	247	25.4	fresh	hard	smooth	clear/sunny	good	4.0 (1.0)
S7	15082017	GS A	27	523	145	21.2	fresh	hard	bumpy	foggy/cloudy	reduced	1.7 (0.6)
S7	15082017	GS B	15	334	110	39.4	fresh	hard	bumpy	foggy/cloudy	reduced	1.7 (0.6)
S8	24082017	GS	35	482	261	24.9	fresh	hard	smooth	clear/sunny	good	−0.3 (0.6)
S8	31082017	GS	34	467	235	20.9	fresh	hard	smooth	clear/sunny	good	5.7 (0.6)
S15	16082017	GS	22	523	133	11.2	fresh	hard	smooth	foggy/snowy	reduced	4.3 (0.6)
S15	24082017	GS	35	482	261	24.9	fresh	hard	smooth	overcast/sunny	good	−0.3 (0.6)
S15	25082017	GS	25	424	199	29.7	fresh	hard	smooth	snowy	reduced	1.3 (0.5)
S16	17092016	GS	28	465	232	27.3	changing	hard	bumpy	foggy/cloudy	good	4.3 (1.5)
S17	14092016	GS	40	517	292	25.1	changing	soft	bumpy	clear/sunny	good	9.3 (1.5)
S18	15092016	GS	29	480	283	29.5	fresh	hard	smooth	snowy	reduced	1.5 (0.6)
S12	20092016	GS	36	872	240	25.1	changing	hard/soft	bumpy	foggy/cloudy	reduced	8.0 (1.0)
S13	21092016	GS	30	711	223	28.4	changing	hard/soft	bumpy	foggy/cloudy	reduced	10.3 (0.6)
S6	16092016	GS	32	465	268	27.8	changing	hard	smooth	clear/sunny	good	5.3 (0.6)
S17	15092016	GS	29	480	283	29.5	fresh	hard	smooth	snowy	reduced	1.5 (0.6)
S11	20092016	GS	36	872	240	25.1	changing	hard/soft	bumpy	foggy/cloudy	reduced	8.0 (1.0)
S18	10092016	GS	31	450	270	31.4	changing	hard	bumpy	foggy/cloudy	reduced	4.3 (0.6)
S6	14092016	GS	40	517	292	25.1	changing	soft	bumpy	clear/sunny	good	9.3 (1.5)

SL, Slalom; GS, Giant Slalom; SG, Super Giant Slalom; DH, Downhill; Alt, altitude; Air t°, air temperature; Drop : vertical drop (m); Incline : mean slope incline in percent. DM: missing data.*mean value for the global course (A + B). Triplet: athletes performed competition-style runs in different disciplines on separate days (i.e., on different slopes and course settings); some skiers were tested once, other multiple times. Thus, a given skier performing a GS on a specific day was considered as a different triplet than the same skier performing a GS (or another discipline) on another day, representing a total of 39 "training sessions x skiers" (triplet with the day of testing, skier, and discipline).

(Spörri et al., 2017). The angle data were derived to compute the joint angular velocity.

Calculations

Cycle and leg determination

The TPM data logger was located on the skier's stomach, under the racing suit and included a 3-axial accelerometer recording at 148 Hz, from which the resultant acceleration (AccR) was determined: $AccR\ (g) = \sqrt{x^2 + y^2 + z^2}$. The AccR was low-pass filtered with a fourth-order Butterworth, cut-off frequencies of 0.8, 1, 2, and 3 Hz for DH, SG, GS, and SL, respectively. The minimal inflection point of the AccR signal derivative was used to identify the turn switch (Nakazato et al., 2011; Kröll et al., 2015b; Spörri et al., 2018) and then the signals were automatically time-normalized to 100% of each leg (Alhammoud et al., 2020). A cycle represented a right turn (IL) plus a left turn (OL), separated by the edge changing phases (between the ranges 0–10, 40–60, and 90–100% of the cycle; Figure 1) (Nakazato et al., 2011). The knee/hip extension and flexion phases were determined from the knee/hip goniometer.

EMG variables

The relative EMG amplitude (RMS %MVC) was computed on the IL and OL for the five muscles after removal of the edge changing phases. The mean power frequency (MPF) was obtained with Fast Fourier Transform. A low-pass filtered EMG (fourth-order Butterworth, cut-off frequencies of 1, 2, 4, and 7 Hz for DH, SG, GS, and SL, respectively) was used to create a linear envelop for the burst duration computation. The EMG activation time was defined as the period where the EMG linear envelope was above 20% of the maximum RMS activity recorded during the MVC (Dorel et al., 2012). The activation time was expressed in absolute time (ms) and relative proportion of the turn (%).

Performance and kinematic variables

The time of each run (chrono) was used as an indicator of performance stability. The turn time (ms) was computed for each leg. The minimal and maximal angles for the right knee and hip were used to compute the amplitude of movement and determine the peak joint angular velocity during the flexion and extension phases.

Statistical analysis

Signal postprocessing was performed through a specifically developed Matlab routine (Matlab 2017a) and statistical comparisons were coded in R (R Foundation for Statistical Computing, Vienna, Austria). A generalized linear mixed model for non-Gaussian response variables distributions was fitted using *glmmTMB* package (Brooks et al., 2017). The EMG activity, angle-related parameters, and turn time were compared between the runs using a generalized linear mixed model with a random effect on the skier-session (ID) and two fixed effects (run with two levels—first and last—and leg with two levels, IL/OL) to evaluate the inter-run effect. For the amplitude and run time parameters, only the run fixed effect was used as the entire cycle (IL + OL) was analyzed. A random intercept model on the skier-session was used within each discipline and for each signal [dependent variable ∼ run + leg + run*leg + (1|ID)]. Based on Akaike Information Criteria and log likelihood (Nakagawa et al., 2017), an algorithm automatically determined the best adjustment for the variables after comparison of normal, lognormal, or gamma distributions. Each model was adjusted based on the best distribution for the considered dependent variable.

Significance was set at $p < 0.05$. The marginal and conditional R^2 were reported as dimensionless standardized effects statistics for linear and generalized linear mixed-effects models (Appendices 1, 2) (Nakagawa et al., 2017; Zhang, 2017). Marginal R^2 (R^2m) is concerned with variance explained by fixed factors while conditional R^2 (R^2c) is concerned with variance explained by both fixed and random factors. The differences between corresponding R^2m and R^2c values reflect how much variability is in random effect (skier-session) compared to the fixed effects (Nakagawa and Schielzeth, 2013) but no cut-off values are available to interpret the magnitude of the effect sizes (ES). As effect sizes for generalized linear mixed models, conditional and adjusted intraclass correlation coefficient (ICC) were computed (Nakagawa et al., 2017), where the grouping (random) factor was the skier-session that has been measured repeatedly as follows:

- ICC_{adj} = random effect variance/(random effect variance + residual variance)
- ICC_{cond} = random effect variance/(random effect variance + residual variance + fixed effect variance)

The random effect variance represents the variability between skier-sessions. The residual variance represents the variability of the measure for a given skier-session. The fixed effect variance is the variability of the fixed effect (run, leg, or both effects). As $R^2m + ICC_{cond} = R^2c$, ICC is another way to present effect sizes obtained with R^2, that varies between 0 and 1. The more ICC is nullified, the less the variability between the skier-sessions is important compared to the variability of the measures for a given skier-session (and compared to the variability of fixed effects for ICC_{cond}). When ICC is close to 1, the dependent variables are more homogenous for a given skier-session than between skier-sessions, and the predictors have no significant effects if we consider ICC_{cond} (see Table 2

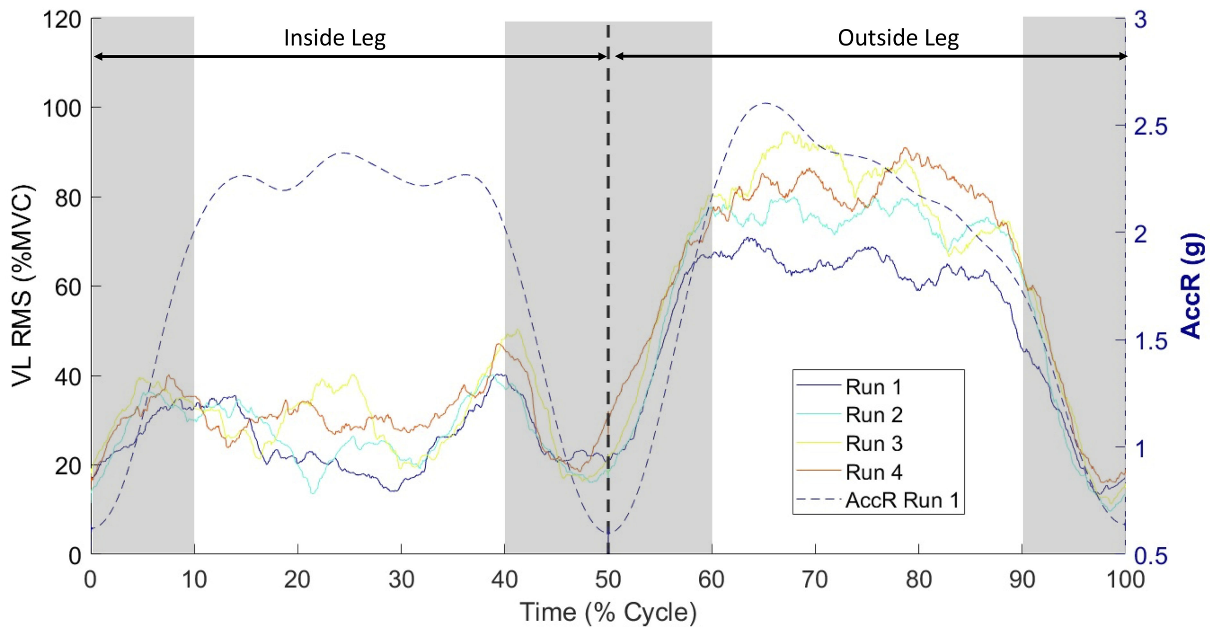

FIGURE 1
Illustration of a time-normalized ski cycle. This double turn is composed of a right turn (i.e., inside leg, IL, 0–50%) and a left turn (i.e., outside leg, OL, 50–100%), for the EMG activity in *vastus lateralis* (VL). Example from one World Cup skier during a session of Giant Slalom from run one to four. Each run represents the average of all cycles within a run (minus the first and last cycles). The shaded gray zones representing the edge changing phases ("unloading" phases ranged 0–10, 40–60, and 90–100% of the cycle) were discarded from the EMG analyses. MVC, maximum voluntary contraction; RMS, EMG amplitude in *root mean square* value over 125-ms epoch. The turn switch is materialized by the black dotted line at 50% of the cycle, at the minima of the resultant acceleration (AccR).

for examples of interpretation). To interpret the significant tests, ICC_{adj} and ICC_{cond} were compared: 1) if $ICC_{adj} \approx ICC_{cond}$, the fixed effect was not large enough (the adjunction of the fixed effect variance to the denominator does not changes the value) and despite a significant *p*-value, it cannot be concluded that there is an effect of the factor on the variable of interest (or the effect is not large enough to be considered; 2) if $ICC_{adj} << ICC_{cond}$ (large difference), we use the cut-off values of Koo and Li (2016) adapted in our context: $ICC_{cond} < 0.5$ very strong fixed ES, $0.5 < ICC_{cond} < 0.75$ strong fixed ES, $0.75 < ICC_{cond} < 0.9$ moderate fixed ES, $ICC_{cond} > 0.9$ small fixed ES.

The values R^2 and ICC represent effect sizes, unlike the coefficient of variation (CV). Three sources of variance were computed in the mixed linear models to describe the data reliability (Appendices 1, 2): (1) the random variance (CV_{random}) represents the variance of the data due to the random factor (skier-session), namely, the dispersion of the measures between the skier-sessions; (2) the intra-athlete variance (CV_{intra}) represents the dispersion of the data for a given skier-session (or "within-group variance"); (3) the systematic variance (CV_{syst}): the higher the CV_{syst}, the higher the chance that run or leg factors would likely be significant (if CV_{random} and CV_{intra} are also high).

The estimated marginal means and confidence intervals at 95% (95%CI) were calculated with *emmeans* package (Lenth, 2019) to take into account the repeated measures and were represented with rainclouds (Allen et al., 2019). The raincloud plots were used as a tool to visualize raw data (a point per turn), probability density (cloud), and key summary statistics (i.e., mean ± 95% CI). Rainclouds allow data visualization with high levels of accuracy and transparency to convey the key aspects of statistical effects and raw data with a minimal distortion (Allen et al., 2019). The data were expressed as mean ± SE in the text.

Results

EMG activation time

The total number of extracted scalar values (i.e., for left and right turns) for EMG signals per muscle was 744 ± 23, 979 ± 13, and 220 ± 0 in SL, GS, and Speed, respectively. The absolute activation time (burst in ms) increased from the first to the fourth run for VM and BF in Speed, for SMST in SL and for VL in GS (all $p \leq 0.024$, $0.18 < ICC_{cond} < 0.84$, moderate to very strong ES; Figure 2; Table 3). There was also an interaction between the run and leg for the SMST in GS, due to a small ($ICC_{cond} = 0.96$) but significant increase on the OL only (+49 ± 19 ms, $p < 0.001$, $R^2m = 0.036$, $R^2c = 1.0$) (Figure 2; Table 2). All activation times were also dependent on the leg ($p < 0.001$,

TABLE 2 *Post hoc* tests of EMG variables and examples of interpretation of ICC as effect sizes for generalized linear mixed models.

Variable	Discipline	Signal	Factor		P value		Effect size			
			Leg	Run	Run	Leg	R^2m	R^2c	ICC_{adj}	ICC_{cond}
RMS	SL	VL	IL	—	0.959	NA	0.000	0.999	0.999	0.999
(%MVC)			OL	—	0.254	NA	0.013	0.999	0.999	0.986
example a			—	First	NA	**0**	0.239	0.999	0.999	0.761
			—	Last	NA	**0**	0.177	1.000	1.000	0.823
	GS	VM	IL	—	0.976	NA		0.999	0.999	0.999
example b			OL	—	**0**	NA	0.043	1.000	1.000	0.957
			—	First	NA	**0**	0.521	1.000	1.000	0.479
			—	Last	NA	**0**	0.524	1.000	1.000	0.476
		SMST	IL	—	0.463	NA	0.002	0.992	0.992	0.990
			OL	—	**0.033**	NA	0.023	0.998	0.998	0.975
			—	First	NA	**0**	0.854	0.999	0.993	0.145
			—	Last	NA	**0**	0.895	0.999	0.990	0.104
Burst	GS	SMST	IL	—	**0**	NA		1.000	1.000	1.000
duration			OL	—	**0**	NA	0.036	1.000	1.000	0.964
(ms)			—	First	NA	**0**	0.681	1.000	1.000	0.319
example c			—	Last	NA	**0**	0.782	1.000	1.000	0.218
	Speed	VM	IL	—	**0.007**	NA	0.069	1.000	1.000	0.931
			OL	—	0.661	NA	0.009	1.000	1.000	0.991
			—	First	NA	**0**	0.400	1.000	1.000	0.600
			—	Last	NA	**0**	0.131	1.000	1.000	0.869
	SL	RF	IL	—	0.535	NA	0.001	0.472	0.471	0.471
example d			OL	—	**0**	NA	0.021	0.491	0.481	0.471
Burst	SL	RF	—	First	NA	**0**	0.206	0.527	0.404	0.321
duration			—	Last	NA	**0**	0.135	0.574	0.508	0.439
(%)	GS	SMST	IL	—	0.444	NA	0.001	0.530	0.530	0.530
			OL	—	**0.011**	NA	0.006	0.531	0.528	0.525
			—	First	NA	**0**	0.276	0.564	0.398	0.288
			—	Last	NA	**0**	0.339	0.569	0.348	0.230

SL, Slalom; GS, Giant Slalom; SG, Super Giant Slalom; DH, Downhill; IL, inside leg; OL, outside leg; NA, not applicable; ICC_{adj}, adjusted intraclass correlation coefficient; ICC_{cond}, conditional intraclass correlation coefficient; R^2m, marginal squared; R^2c, conditional R-squared; significant p-values ($p < 0.05$) are indicated in bold, trend ($0.05 \leq p \leq 0.01$) in italic and bold.

Example a: For RMS of VL in SL, leg effect: $ICC_{cond} = 0.761$, $ICC_{adj} = 0.999$, $p \approx 0$. The fact that ICC_{adj} approaches 1 shows that RMS is more homogenous for a given skier-session than between skier-sessions. Besides, $ICC_{cond} < ICC_{adj}$ and the addition of leg fixed effect diminishes ICC of roughly 25%. Hence, the effect size of the leg on RMS of VL in SL is moderate, nearly strong.

Example b: For RMS of VM in GS, run effect on OL: $ICC_{cond} = 0.957$, $ICC_{adj} = 0.999$, $p \approx 0$. The fact that ICC_{adj} approaches 1 shows a greater variability between the skier-sessions compared with measures done on the same skier-session. Besides, ICC_{cond} is slightly lower than ICC_{adj}. Despite a significant p-value, we can therefore conclude that the effect size of the run on OL on RMS for VM in GS is very small.

Example c: For the absolute burst duration of SMST in GS, leg effect on the last run: $ICC_{cond} = 0.218$, $ICC_{adj} = 1.000$, $p \approx 0$. The value of ICC_{adj} indicates that there is no variability for this variable in the measurements of a given skier-session. Additionally, the fact that $ICC_{cond} < ICC_{adj}$ confirms the significance of the test namely there is a very strong leg effect on the fourth run for this variable.

Example d: For the relative burst duration of RF in SL, run effect on OL: $ICC_{cond} = 0.471$, $ICC_{adj} = 0.481$, $p \approx 0$. The value of ICC_{adj} indicates that there is nearly as much variability in the measurements of this variable between skier-sessions than for a given skier-session. Additionally, $ICC_{cond} \approx ICC_{adj}$, consequently despite a quasi-null p-value, we cannot conclude that there is a run effect of this variable on OL.

$0.106 \leq R^2m \leq 0.808$, $0.18 < ICC_{cond} < 0.85$, moderate to very strong ES) except for the BF in SL ($p = 0.266$). There were higher values of absolute activation time on IL compared to OL for RF and greater values on OL than IL for the other muscles.

When expressed relatively to the cycle duration (burst in %), there was no difference between the first and the fourth run for any muscles and disciplines ($p \geq 0.057$) but there was an interaction run*leg for SMST in GS and for RF in SL ($p \leq 0.037$; Figure 2). These interactions were due to an increase of the relative duration of the burst on the OL albeit not clinically relevant (SMST in GS: $+3.7 \pm 1.4\%$, $p = 0.011$, $R^2m = 0.006$, $R^2c = 0.531$, $ICC_{cond} \approx ICC_{adj}$, negligible ES; RF in SL: $p <$

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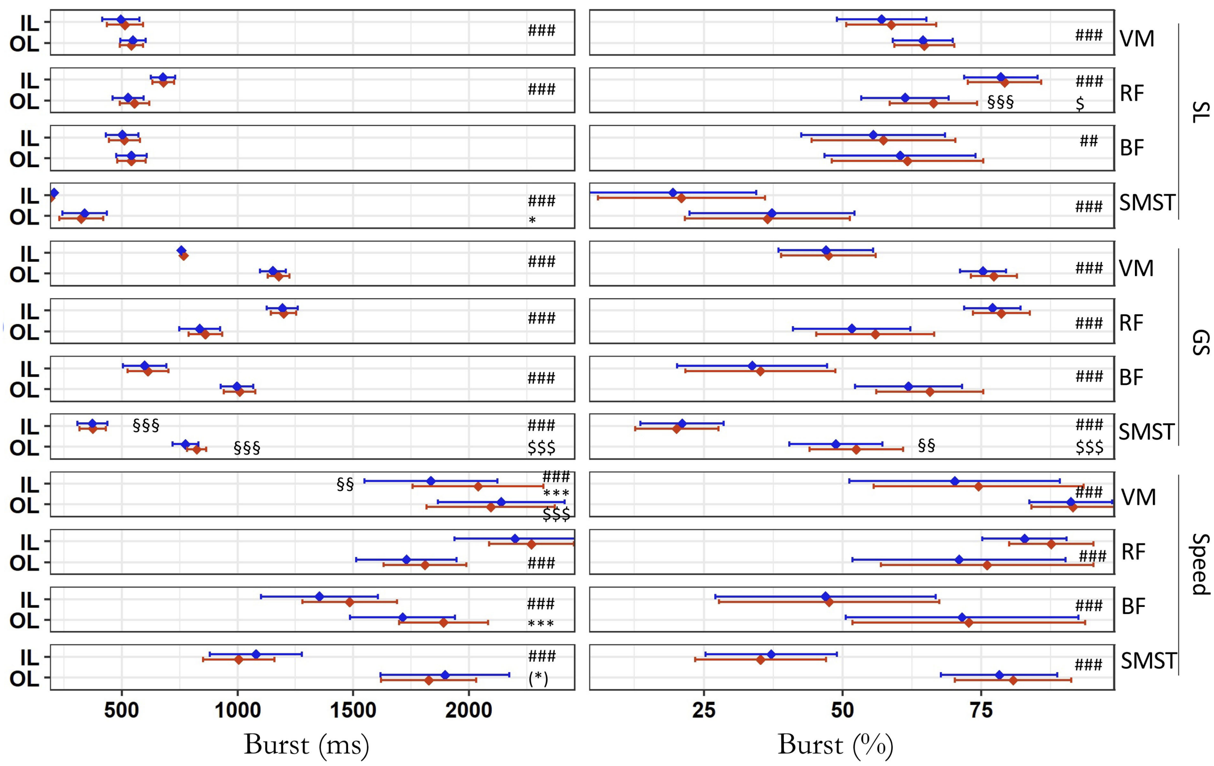

FIGURE 2
Activation time during the first (blue) and last (red) run across all skier-sessions ($n = 39$). Left: absolute values in ms. Right: relative values in percentage of the turn duration. Values are mean and 95% confidence intervals for the inside (IL) and outside (OL) leg. SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill; VM, *vastus medialis*; RF, *rectus femoris*; BF, *biceps femoris*; SMST, *semi-membranosus – semi tendinosus*. Due to the similarities between both *vastii*, only the medial head is represented. # difference between IL and OL, * difference between first and last run, $ interaction effect, §*Post hoc* of the interaction showing the difference between first and last run on a single leg. ***, ###, $$$, §§§$p < 0.001$; §§, ## $p < 0.01$; *, $ $p < 0.05$; (*) $p < 0.10$. The raincloud plot visualizes raw data (one point per right and left turn, i.e., inside and outside leg, respectively), probability density (cloud), and key summary statistics of the mean ± 95% confidence intervals. Each skier-session counts a certain amount of turns (right turn, inside leg; left turn, outside leg) composing run one and four. Each individual dot represents the value of the variable for a given right and left turn (inside and outside leg, respectively). The dotted line in blue and red between the two rainclouds of each discipline's subplot links the inside and outside legs of the first and last run, respectively.

0.001, $R^2m = 0.021$, $R^2c = 0.491$, $ICC_{cond} \approx ICC_{adj}$, negligible ES), but not on the IL (SMST in GS: $-1.0 \pm 1.3\%$, $p = 0.444$; RF in SL: $+0.7 \pm 1.1\%$, $p = 0.535$). All relative activation times strongly depended on the leg ($p < 0.002$, $ICC_{cond} < 0.72$) with greater values of the relative burst duration on IL than OL for RF but an opposite pattern for the SMST, BF, VM, and VL.

EMG activation level

The EMG activity increased from the first to the fourth run for the VM in SL ($p = 0.035$, $ICC_{cond} = 0.86$, moderate ES) and GS ($p < 0.001$, $ICC_{cond} = 0.47$, very strong ES) and the VL in Speed ($p < 0.001$, $ICC_{cond} = 0.22$, very strong ES). There was an interaction leg*run for the VL in SL and the VM and SMST in GS ($p \leq 0.044$; Figure 3; Table 4). *Post hoc* analyses (Table 2) revealed that the VM ($+6.7 \pm 1.2\%$ MVC) and SMST ($+1.5 \pm 0.7\%$ MVC) increased their activation only in GS and only on the OL ($p \leq 0.033$, $R^2m \leq 0.043$, $R^2c \geq 0.998$, $0.95 < ICC_{cond} < 0.98$, very small ES), while the difference did not reach significance for the VL in SL (OL $p = 0.254$, IL $p = 0.959$). All EMG activities but the BF in SL ($p = 0.204$) depended on the leg with higher values on the OL than IL ($p \leq 0.001$), except for the RF where the IL activity was higher than the OL activity ($p < 0.001$) in all disciplines. The effects of leg were moderate to very strong ($p < 0.001$, $0.141 \leq R^2m \leq 0.928$, $0.07 < ICC_{cond} < 0.86$).

The CV_{intra} between the first and fourth run among all skiers was 0.6% for RMS (averaged across five muscles and three disciplines). A CV_{random} of 16.8% (range, 9.2–27.8%) for RMS (across five muscles and three disciplines) was found when looking at the repeatability between the skier-sessions (Appendix 2).

TABLE 3 Comparison of EMG burst duration during the first and last run for five muscles.

Variable	Discipline	Signal	*P* value			Effect size		*Emmean diff.* Last-First [95%CI]	
			Run	Leg	Run*Leg	ICC_{adj}	ICC_{cond}	OL	IL
Burst duration (ms)	SL	VM	0.185	**0.001**	0.160	1.000	0.803	−6.3 [−34.4; 21.8]	17.1 [−10.3; 44.5]
		VL	0.880	**0.000**	0.113	1.000	0.728	−23.2 [−53; 6.6]	3.3 [−24.2; 30.7]
		RF	0.844	**0.000**	0.106	1.000	0.335	27.8 [2.3; 53.2]	1.3 [−28.1; 30.7]
		BF	0.524	0.266	0.691	1.000	0.990	0.1 [−26.5; 26.8]	9.3 [−17.3; 35.8]
		SMST	**0.024**	**0.000**	0.758	1.000	0.771	−14.9 [−43.1; 13.3]	−16.8 [−28; −5.6]
	GS	VM	0.695	**0.000**	0.450	1.000	0.188	25 [−10.4; 60.4]	10 [−31; 51]
		VL	**0.018**	**0.000**	***0.057***	1.000	0.182	−2.9 [−37.1; 31.2]	39.7 [−2.7; 82.1]
		RF	0.548	**0.000**	0.808	1.000	0.264	24.7 [−22.8; 72.1]	5.5 [−37.7; 48.8]
		BF	0.940	**0.000**	0.242	1.000	0.327	11.8 [−21.1; 44.7]	14.9 [−16.7; 46.6]
		SMST	0.612	**0.000**	**0.000**	1.000	0.245	49.3 [11.4; 87.1]	0.5 [0.5; 0.5]
	Speed	VM	**0.000**	**0.001**	**0.000**	1.000	0.661	−45.4 [−172.6; 81.8]	203.8 [54.9; 352.7]
		VL	0.249	**0.000**	0.546	1.000	0.675	5.5 [−93.1; 104]	60 [−166.7; 286.6]
		RF	0.179	**0.000**	0.717	1.000	0.442	80 [−60; 220.1]	71.2 [−93.9; 236.3]
		BF	**0.001**	**0.000**	0.562	1.000	0.843	176.7 [28.5; 324.8]	130.6 [−21.7; 283]
		SMST	***0.057***	**0.000**	0.268	1.000	0.171	−70.1 [−216.5; 76.4]	−75.5 [−230.3; 79.3]
Burst duration (%)	SL	VM	0.161	**0.000**	0.368	0.406	0.387	0.3 [−2; 2.5]	1.7 [−1; 4.4]
		VL	0.422	**0.000**	0.715	0.319	0.300	0.4 [−1.8; 2.5]	1 [−1.6; 3.6]
		RF	0.582	**0.000**	**0.012**	0.446	0.366	5.1 [2.6; 7.7]	0.7 [−1.5; 2.9]
		BF	0.175	**0.002**	0.789	0.723	0.716	1.3 [−1.1; 3.8]	1.8 [−0.9; 4.6]
		SMST	0.330	**0.000**	0.293	0.670	0.616	−0.8 [−4.2; 2.5]	1.6 [−0.9; 4]
	GS	VM	0.728	**0.000**	0.442	0.390	0.249	1.9 [0.4; 3.5]	0.5 [−2.6; 3.5]
		VL	0.162	**0.000**	0.632	0.443	0.276	1.2 [−0.3; 2.7]	1.6 [−1.5; 4.7]
		RF	0.292	**0.000**	0.221	0.431	0.336	4.3 [1.3; 7.2]	1.6 [−0.7; 3.9]
		BF	0.322	**0.000**	0.297	0.621	0.483	3.9 [1.4; 6.3]	1.5 [−1; 4]
		SMST	0.529	**0.000**	**0.037**	0.374	0.258	3.7 [0.8; 6.5]	−1 [−3.5; 1.5]
	Speed	VM	0.109	**0.000**	0.300	0.554	0.455	0.4 [−3; 3.8]	4.3 [−1.2; 9.9]
		VL	***0.057***	**0.000**	0.456	0.493	0.374	2.5 [−0.1; 5.1]	5.5 [−0.9; 11.9]
		RF	0.191	**0.001**	0.958	0.380	0.353	5.1 [−1.8; 11.9]	4.8 [−1.1; 10.7]
		BF	0.880	**0.000**	0.900	0.619	0.533	1.2 [−4.7; 7.1]	0.7 [−7.5; 8.8]
		SMST	0.617	**0.000**	0.411	0.236	0.127	2.5 [−4.2; 9.3]	−1.9 [−9.8; 6]

OL, outside leg; IL, inside leg; SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill; ICC_{adj}, adjusted intraclass correlation coefficient; ICC_{cond}, conditional intraclass correlation coefficient; Emmean diff.: estimated marginal mean of the difference between the last and first run. See Appendix 2 for detailed R squared values and coefficients of variation. Significant p-values ($p < 0.05$) are indicated in bold, trend ($0.05 \leq p \leq 0.01$) in italic and bold.

Mean power frequency

The EMG mean power frequency did not statistically differ between the first and fourth run ($p \geq 0.082$), except for an increase for the RF in GS (IL: +3 ± 0.7 Hz, OL: +1.9 ± 0.9 Hz; $p = 0.003$, $R^2m = 0.457$, $R^2c = 0.999$, $ICC_{cond} = 0.54$, strong ES; Figure 4). There was no significant interaction between run and leg for the five muscles across the three disciplines ($p \geq 0.170$). There was a main effect of the leg for all disciplines and muscles ($p \leq 0.007$, $0.129 \leq R^2m \leq 0.927$, $0.07 < ICC_{cond} < 0.88$, moderate to very strong ES; except for RF in Speed $p = 0.054$), due to the higher values on OL compared to IL for all muscles, but RF where the opposite pattern was seen (IL > OL).

Performance and kinematic variables

There were no changes in run time (chrono) from the first to the fourth run ($p > 0.158$) except in SL (−0.44 ± 0.14 s; p =0.002; Table 5), but this effect was not meaningful (i.e., negligible effect size $R^2m < 0.001$, and large variability in the random effect $R^2c > 0.999$). There were no changes in turn time from the first to the fourth run ($p \geq 0.487$; Table 5).

The total number of turns analyzed for each angle-related parameter of the knee/hip (for left and right turns) was 587/485, 859/801, and 216/110 in SL, GS, and Speed, respectively. There were no significant changes in the amplitude of movement from

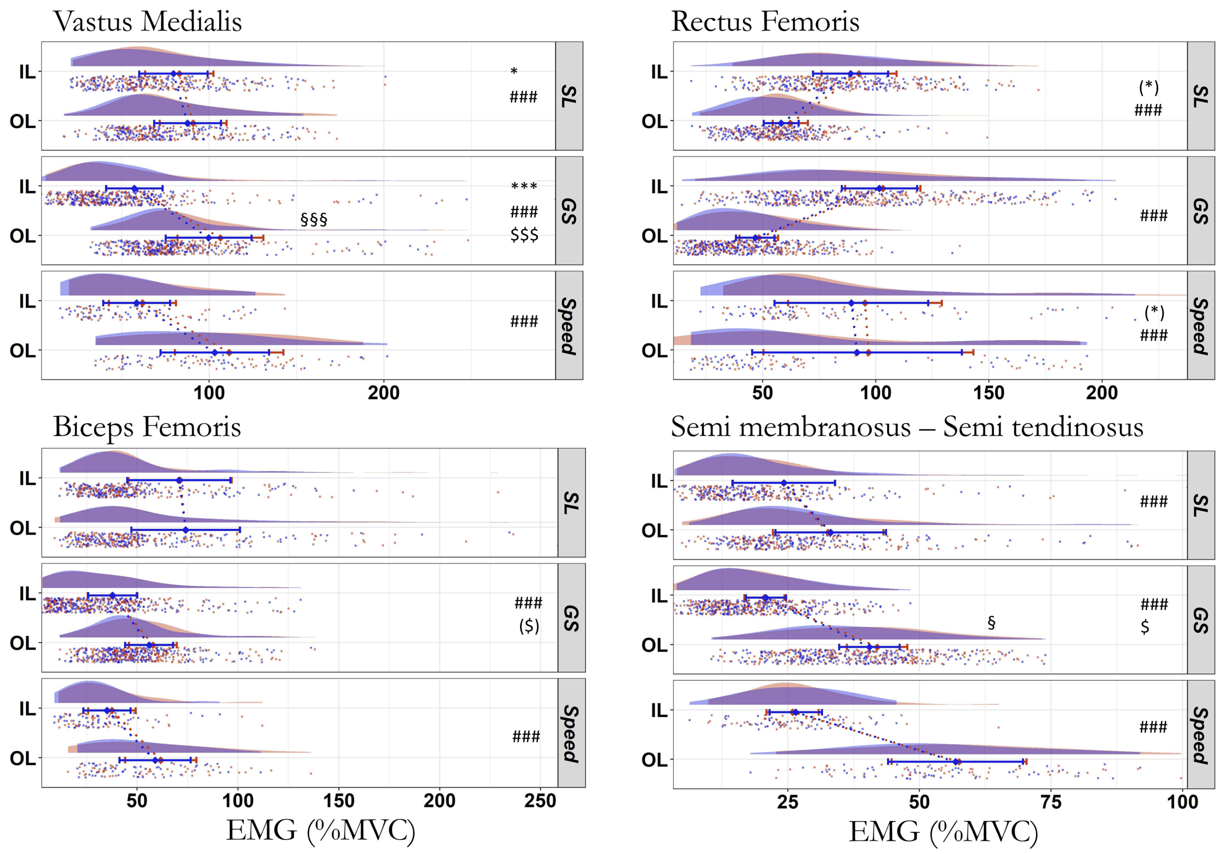

FIGURE 3
Electromyographic (RMS) activity during the first (blue) and last (red) run across all skier-sessions ($n = 39$). Values are RMS activity in percentage of MVC for the inside (IL) and outside (OL) leg. Due to the similarities between both *vastii*, only the medial head is represented. SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill. #Difference between IL and OL, * difference between first and last run, $ interaction effect, §*Post hoc* of the interaction showing the difference between first and last run on a single leg. ***, ###, §§§, $$$ $p < 0.001$; *, $, § $p < 0.05$; ($), (*) $p < 0.10$. The raincloud plot visualizes raw data (one point per right and left turn, i.e., inside and outside leg, respectively), probability density (cloud), and the key summary statistics of the mean ± 95% confidence intervals. Each skier-session counts a certain number of turns (right turn, inside leg; left turn, outside leg) composing run one and four. Each individual dot represents the value of the variable for a given right and left turn (inside and outside leg, respectively). The dotted line in blue and red between the two rainclouds of each discipline's subplot links the inside and outside legs of the first and last run, respectively.

the first to the fourth run for all joints and disciplines (all $p > 0.106$, $R^2m \leq 0.006$; Figure 5). The maximal and minimal angles did not change for any joint in any discipline ($p > 0.257$; Figure 6) except for the maximal knee and hip angles in SL ($p \leq 0.024$, $ICC_{cond} < 0.50$, very strong ES). The changes in the maximal hip angle in SL depended on the leg (interaction leg*run: $p = 0.007$, $R^2 = 0.354$, $R^2c = 0.781$), with both non-significant values decrease on the IL ($-1.9 \pm 1.0°$, $p = 0.060$) and increase on the OL ($+1.1 \pm 1.0°$, $p = 0.306$). The interaction run*leg did not reach significance for the knee ($p = 0.052$; IL: $-3.4 \pm 1.2°$ and OL: $+0.4 \pm 1.2°$), despite a decrease in knee maximal angle in IL only ($p = 0.015$, $ICC_{cond} = 0.1$, very strong ES). There was a strong to very strong fixed ES ($ICC_{cond} < 0.68$) of leg for all joints angles across all disciplines ($p < 0.001$, $0.136 < R^2m < 0.973$).

The peak angular velocity of the hip and knee did not change from the first to the fourth run during both the extension ($p > 0.141$) and flexion ($p > 0.482$) phases in any joint and discipline (Table 6), except for SL showing a very large increase ($ICC_{cond} = 0.17$) in knee (IL: $15.2 \pm 5.7°\ s^{-1}$; OL: $12.8 \pm c7.8\ s^{-1}$) and a strong increase ($ICC_{cond} = 0.52$) in hip (IL: $11.2 \pm 5.5\ s^{-1}$; OL: $22.1 \pm 7.0\ s^{-1}$) peak extension velocity ($p \leq 0.025$, $R^2m \geq 0.482$, $R^2c = 1.0$). There was also an effect of leg in SL with higher absolute values on OL during the flexion and extension phases ($p < 0.001$; Figure 7) but not in other disciplines.

When calculating the repeatability between two runs (first and fourth), the CV_{intra} was 7.8% and 0.1% among all athletes for maximal and minimal knee angle, respectively (knee and hip averaged across three disciplines). The CV_{random} for the repeatability between the skier-sessions were 7.4 and 4.8% for

TABLE 4 Comparison of EMG activity during the first and last run for five muscles.

Variable	Discipline	Signal	*P* value			Effect size		*Emmean diff.* Last-First [95%CI]	
			Run	Leg	Run*Leg	ICC_{adj}	ICC_{cond}	OL	IL
RMS (%MVC)	SL	VM	**0.035**	**0.000**	0.943	1.000	0.859	3.2 [0; 6.4]	3.4 [0.2; 6.6]
		VL	0.349	**0.000**	**0.044**	0.999	0.720	2.3 [−1.7; 6.3]	−0.1 [−4.1; 3.9]
		RF	***0.063***	**0.000**	0.985	0.999	0.239	4.1 [1.3; 6.9]	3.7 [0.7; 6.7]
		BF	0.533	0.204	0.693	1.000	0.997	−0.1 [−1.8; 1.6]	0.6 [−1; 2.2]
		SMST	0.798	**0.000**	0.787	0.997	0.636	−0.5 [−1.9; 0.9]	−0.1 [−0.8; 0.7]
	GS	VM	**0.000**	**0.000**	**0.000**	1.000	0.465	6.7 [4.4; 8.9]	0 [−2.7; 2.8]
		VL	0.367	**0.000**	0.174	0.999	0.286	5.2 [3; 7.4]	0.8 [−1.9; 3.4]
		RF	0.583	**0.000**	0.891	0.998	0.129	1.6 [−0.4; 3.6]	1.5 [−1.9; 4.9]
		BF	0.474	**0.000**	***0.090***	0.999	0.381	1.9 [0.5; 3.2]	−0.3 [−1.1; 0.5]
		SMST	0.441	**0.000**	**0.030**	0.990	0.100	1.5 [0.1; 2.8]	−0.3 [−1.1; 0.5]
	Speed	VM	0.123	**0.000**	0.125	0.999	0.359	8.3 [2.4; 14.2]	3.3 [−1.7; 8.4]
		VL	**0.015**	**0.000**	0.278	0.999	0.221	10.6 [4.7; 16.5]	5.6 [0.3; 11]
		RF	***0.078***	**0.000**	0.837	1.000	0.839	5.1 [0.4; 9.8]	6.1 [−1.2; 13.3]
		BF	0.123	**0.000**	0.686	0.998	0.533	2.8 [−0.7; 6.3]	2.5 [−0.8; 5.7]
		SMST	0.591	**0.000**	0.447	0.995	0.071	0.7 [−2.9; 4.2]	−0.6 [−3.6; 2.3]
MPF (Hz)	SL	VM	0.291	**0.000**	0.407	1.000	0.404	2.3 [0.3; 4.2]	1 [−0.5; 2.5]
		VL	0.585	**0.007**	0.170	1.000	0.871	1.6 [−0.3; 3.5]	−0.6 [−3.3; 2.1]
		RF	0.126	**0.000**	0.309	0.999	0.213	4.6 [2.6; 6.5]	2.2 [0.6; 3.8]
		BF	0.820	**0.003**	0.841	0.999	0.867	0 [−2.5; 2.5]	0.3 [−1.9; 2.6]
		SMST	0.866	**0.000**	0.959	1.000	0.525	0.4 [−3; 3.7]	−0.2 [−2.7; 2.4]
	GS	VM	***0.082***	**0.000**	0.598	1.000	0.278	2.2 [1; 3.5]	1.4 [−0.3; 3.1]
		VL	0.120	**0.000**	0.967	1.000	0.706	2.7 [1.2; 4.3]	1.6 [−1; 4.2]
		RF	**0.003**	**0.000**	0.416	0.999	0.542	1.9 [0.2; 3.6]	3 [1.6; 4.3]
		BF	0.871	**0.000**	0.221	0.999	0.147	1.7 [−0.1; 3.6]	−0.2 [−2; 1.6]
		SMST	***0.091***	**0.000**	0.976	1.000	0.333	1.9 [−0.1; 3.9]	1.7 [−0.5; 3.9]
	Speed	VM	0.800	**0.000**	0.337	0.999	0.392	−2.3 [−6.1; 1.5]	0.6 [−2.5; 3.6]
		VL	0.601	**0.000**	0.939	0.999	0.337	0.5 [−2.2; 3.3]	0.9 [−2.6; 4.4]
		RF	0.734	***0.054***	0.563	0.998	0.589	0.8 [−1.6; 3.2]	−0.6 [−2.9; 1.7]
		BF	0.736	**0.000**	0.753	0.996	0.073	−0.2 [−2.8; 2.5]	−0.8 [−3.1; 1.4]
		SMST	0.207	**0.000**	0.328	1.000	0.187	−0.6 [−3.6; 2.5]	2.8 [−1.4; 7.1]

OL, outside leg; IL, inside leg; SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill; RMS, root mean square value of the EMG; MPF, mean power frequency; ICC_{adj}, adjusted intraclass correlation coefficient; ICC_{cond}, conditional intraclass correlation coefficient; Emmean diff.: estimated marginal mean of the difference between the last and first run. See Appendix 2 for detailed R squared values and coefficients of variation. Significant p-values ($p < 0.05$) are indicated in bold, trend ($0.05 \leq p \leq 0.01$) in italic and bold.

maximal and minimal knee angle, respectively (knee and hip averaged across three disciplines; Appendix 1).

Discussion

This study examined the impact of repeated ski runs on leg muscle electromyographic activity in elite alpine skiers for three disciplines. The original hypothesis that minimal EMG activity adjustments would occur with runs repetition to maintain the skier performance and technique was globally supported, as evidenced by the low coefficients of variations. The data showed only a few marginal EMG adjustments (e.g., increase VM activity in SL and GS, increase in VL activity in Speed), without changes in the skier performance (i.e., run time and turn time) from the first to the fourth run. There were no differences in EMG mean power frequency between the first and fourth run (except RF in GS); therefore, the neuromuscular characteristics remain highly stable in elite skiers with low variability across four runs.

Muscle activity

This study showed some decreases (SMST in SL and GS, VM in Speed) as well as increases (VL in GS, BF in Speed) and in absolute activation time (Figure 2). The latter could suggest a

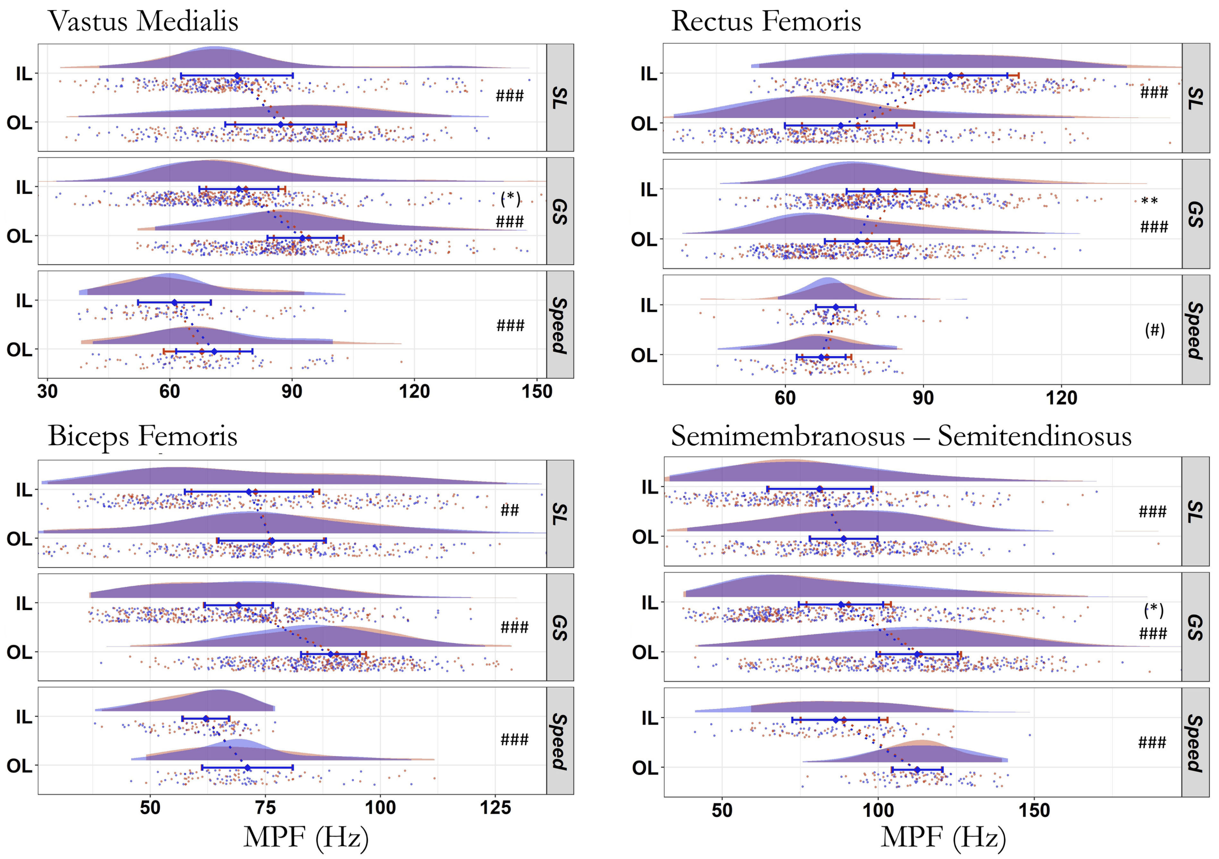

FIGURE 4
Median Power Frequency (MPF) of the electromyographic activity during first (blue) and last (red) run across all skier-sessions ($n = 39$). MPF values in Hz for the inside (IL) and outside (OL) leg. Due to the similarities between both *vastii*, only the medial head is represented. SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill. #Difference between IL and OL, *difference between first and last run. ### $p < 0.001$; **, ## $p < 0.01$; (#), (*) $p < 0.10$. The raincloud plot visualizes raw data (one point per right and left turn, i.e., inside or outside leg, respectively), probability density (cloud), and key summary statistics of the mean ± 95% confidence intervals. Each skier-session counts a certain amount of turns (right turn, inside leg; left turn, outside leg) composing run one and four. Each individual dot represents the value of the variable for a given right and left turn (inside and outside leg, respectively). The dotted line in blue and red between the two rainclouds of each discipline's subplot links the inside and outside legs of the first and last run, respectively.

change in the contraction-relaxation cycle with the skiers having more difficulty to relax as runs were repeated. Importantly, the relaxation ability between turns at the right timing is a key performance factor (Pfefferlé, 2014) as muscle de-recruitment permits recovery, enhanced blood flow and efficient movement sequence (Szmedra et al., 2001). Dorel et al. (2012) showed that the longer period of activity induced during sprint in cycling is likely to represent a coordination strategy to enhance the work generated by all the muscle groups. However, the absolute burst duration modifications observed during this study remained inconsistent across muscles, legs and disciplines with opposite variations. Moreover, most of these changes disappeared when the EMG signal was expressed relatively to the cycle duration except marginal increases due to an interaction run*leg for RF in SL and for SMST in GS (OL: ∼+4–5% relative burst duration; Figure 2; Table 3). Those changes were of low magnitude with negligible ES on the OL for both ($p \leq 0.011$ but $ICC_{adj} \approx ICC_{cond}$, Table 2), mainly due to the intra-skier variability (high R^2c) with low clinical relevance (low R^2m; Appendix 1). Indeed, in contrast to intermediate skiers, a regular muscle activation pattern (VM and BF) with clear switching between IL and OL has been reported in experienced skiers regardless of number of turns (Kiryu et al., 2011). This is also in line with the observation that the expert skiers were able to maintain their posture despite fatigue occurrence (Akutsu et al., 2008). The ability of athletes to maintain consistency in muscle synergy despite changes in torque and posture was also previously reported in other sports such as highly trained cyclists (Hug et al., 2011). The stability of the neuromuscular pattern in elite skiers is further confirmed in this study by the very low intra-skier variability (Appendix 1), as shown by a CV_{intra} ranging from 0.3 to 1.2% for RMS.

TABLE 5 Run time and turn time.

Variable	Discipline	*P* value			Effect size				Factor	Emmean [95%CI]		
		Run	Leg	Run*Leg	R^2m	R^2c	ICC_{adj}	ICC_{cond}		First	Last	Last - First
Run time (s)	SL	**0.002**	–	–	0.001	0.999	–	–	Run	34.90 [28.04; 41.76]	34.47 [27.61; 41.32]	−0.44 [−0.77; −0.10]
	GS	0.158	–	–	0.010	0.876	–	–	Run	50.96 [47.44; 54.48]	49.56 [46.09; 53.03]	−1.40 [−3.55; 0.75]
	Speed	0.199	–	–	0.007	0.943	–	–	Run	40.87 [39.52; 42.22]	40.59 [39.24; 41.95]	−0.28 [−0.78; 0.23]
Turn time (ms)	SL	0.487	**0.031**	0.478	0.007	0.053	0.050	0.050	OL	787 [754; 821]	805 [771; 841]	−19 [−48; 11]
									IL	822 [786; 860]	822 [785; 860]	1 [−34; 35]
	GS	0.806	0.385	0.759	0.001	0.034	0.030	0.030	OL	1,461 [1,410; 1,515]	1,471 [1,419; 1,525]	−10 [−51; 31]
									IL	1,476 [1,428; 1,526]	1,475 [1,427; 1,525]	1 [−40; 42]
	Speed	0.986	***0.066***	0.586	0.014	0.160	0.150	0.150	OL	2,147 [1,953; 2,360]	2,192 [1,994; 2,410]	−45 [−229; 139]
									IL	2,372 [2,073; 2,713]	2,324 [2,032; 2,658]	48 [−202; 298]

OL, outside leg; IL, inside leg; SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill; ICC_{adj}, adjusted intraclass correlation coefficient; ICC_{cond}, conditional intraclass correlation coefficient; R^2m, marginal squared; R^2c, conditional R squared; Emmean: estimated marginal mean. Significant p-values ($p < 0.05$) are indicated in bold, trend ($0.05 \leq p \leq 0.01$) in italic and bold.

The raincloud representation of the RMS activity (Figure 3) showed that RMS data distribution were skewed (highly concentrated on the left and spread out on the right). This further justified the use of generalized linear mixed models as residuals were not normally distributed but instead close to a gamma law. The statistical analyses showed a main run effect with an increase in RMS for the *vastii* (VM in GS on OL, VL in Speed on both legs, VM in SL on both legs; Table 4), along a trend for RF in SL ($p = 0.063$) and Speed ($p = 0.078$). This emphasizes the key role of the quadriceps in alpine skiing whatever the discipline (Figure 3). We observed a specific increase in medial hamstrings (SMST) on the OL only in GS, but its effect size was small ($ICC_{cond} = 0.975$; Table 2) with a limited clinical relevance (+1.5% MVC). The limited increases in EMG activity from the first to the fourth run may suggest some neuromuscular adjustments due to peripheral disturbances, although this explanation is less likely as there was enough inter-set recovery time. This is consistent with the fact that central fatigue is considered to recover quickly (Carroll et al., 2017) and was possibly present at the end of each run but subsequently recovered in the 20–30 min period separating the runs.

None of the MPF changes from the first to the fourth run (Figure 4) reached significance in this study ($p \geq 0.082$ for VM and SMST in GS), except for the RF in GS on both legs where a modest increase was seen (∼+2–3 Hz; $p = 0.003$, moderate ES; Table 4). However, the practical implications are not known. Regardless of any "inter-run" effect, it is worth noting that we observed higher values of MPF on the OL compared to IL for all muscles except RF where the opposite pattern was seen (IL > OL), whatever the discipline. This indicates a strong preferential and asymmetrical OL use in alpine ski racing, although an important co-loading of the IL for VL has previously been reported in ski carving (Müller and Schwameder, 2003). The biarticular RF showed a marked EMG intensity and MPF on the IL and also on the OL albeit to a lesser extent. Similarly, previous results show higher myoelectric frequency for the VL and RF on the OL and IL, respectively (Kröll et al., 2011), along with marked differences between legs (Kröll et al., 2010). Interestingly, GS has also been reported to induce a greater muscle oxygen desaturation than SL (Szmedra et al., 2001) as the skiers maintain a lower posture and thus, probably a greater static load with higher percentage of MVC on OL (Figure 3), consistent with compromised blood flow to the VL (Szmedra et al., 2001). Such local hypoxia can impair neural drive during rapid contractions in elite skiers, but this effect could also be blunted by the larger effect of fatigue when contractions are repeated (Alhammoud et al., 2018). The high level of activity of all muscle fibers during alpine skiing could hypothetically induce an ischaemic environment that would result in a decreased neural drive (Ferguson, 2010). Nevertheless, voluntary activation recovers within 3 min of blood flow restoration (Woods et al., 1987), i.e., a duration shorter than the inter-run interval. Thus, while skiing may induce muscle ischemia and hypoxia leading to an intra-run fatigue, no inter-run EMG changes were visible. This absence of changes may partly be related to recovery between runs. It should also be considered that athletes who repeatedly perform high-force intermittent exercise with short rest periods such as skiers or climbers have an adapted vasculature to enhance the blood flow response limiting this fatigue effect (Ferguson and Brown, 1997; Ferguson, 2010). Finally, the absence of inter-run EMG changes may be partly due to a lack of sensitivity of the values such as activation time or average EMG activity. Indeed, the reduction of the turn to one scalar value collapses the temporal aspects of the signal and potentially hinders important information such as shift of EMG activation onset/offset (Figure 1). Since the EMG changes were not large enough to be detected by traditional statistics, more sensitive analyses such as Statistical Parametric Mapping (SPM) (Alhammoud et al.,

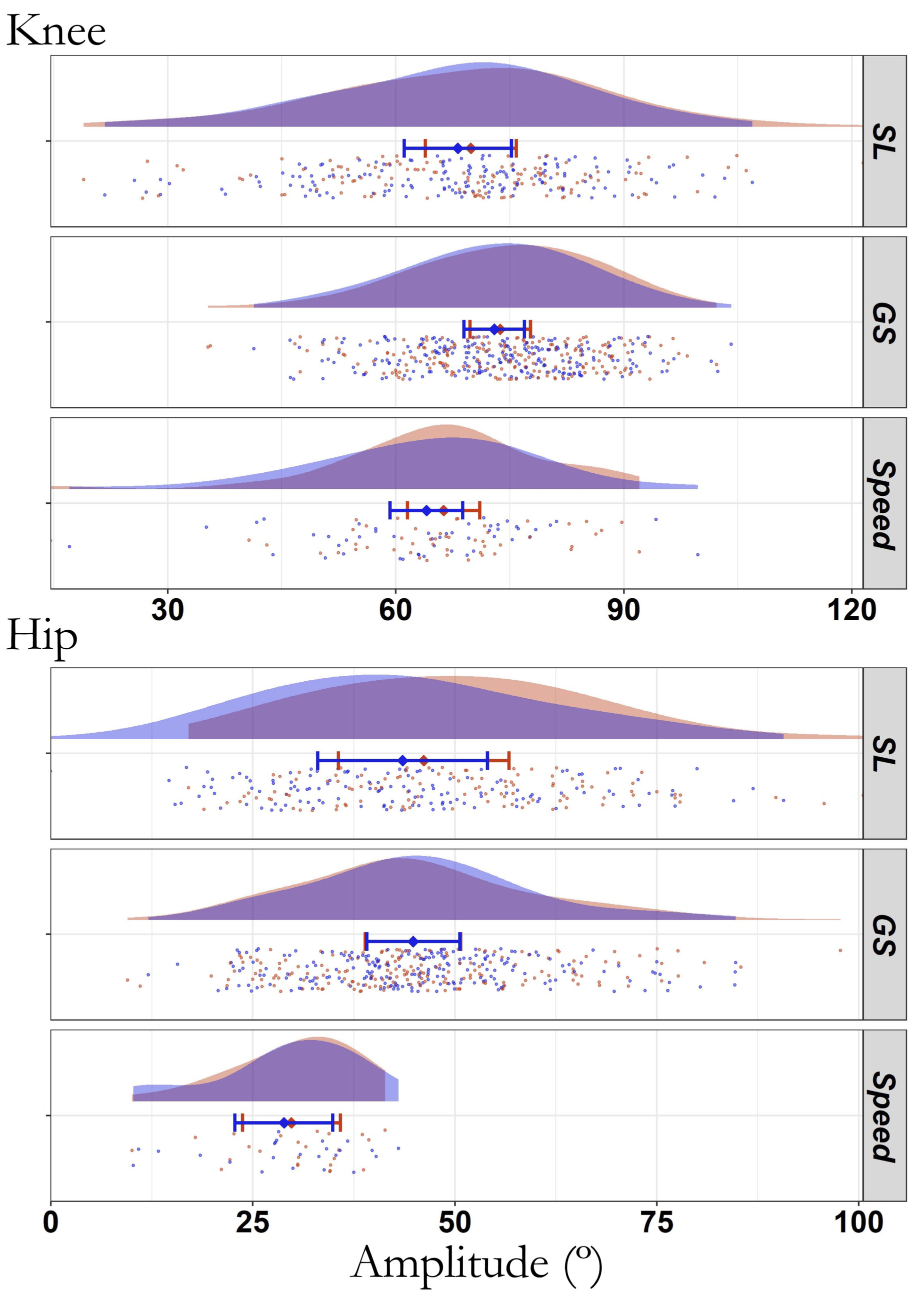

FIGURE 5
Raincloud of the average amplitude of movement in degrees for the knee and hip (180° full extension) during the first (blue) and last (red) run across all skier-sessions ($n = 39$). SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill. No statistical differences between first and last run (all $p \geq 0.106$). The raincloud plot visualizes raw data (a point per cycle), probability density (cloud), and key summary statistics of the mean ± 95% confidence intervals. Each skier-session includes a certain number of cycles (double turns) composing runs one and four. Each individual dot represents the value of the amplitude for a given cycle, i.e., a double turn with an inside plus outside leg turn. SL Slalom, GS Giant Slalom, Speed Super Giant Slalom and Downhill. No statistical differences between first and last (all $p \geq 0.106$).

2019) and wavelet transform should be applied on the entire turns' signal.

In our on-field study, some neuromuscular adjustments (e.g., increases in *vastii* RMS activity) may have resulted from the influence of external factors, such as the evolution of the ski-snow properties. Indeed, the snow conditions changed in 41% of the sessions, generally toward a warmer state (Table 1). While there was minimal track deterioration with regular sleepers between skiers, a softer snow may have induced lower EMG activity levels (Federolf et al., 2009), partly blunting a

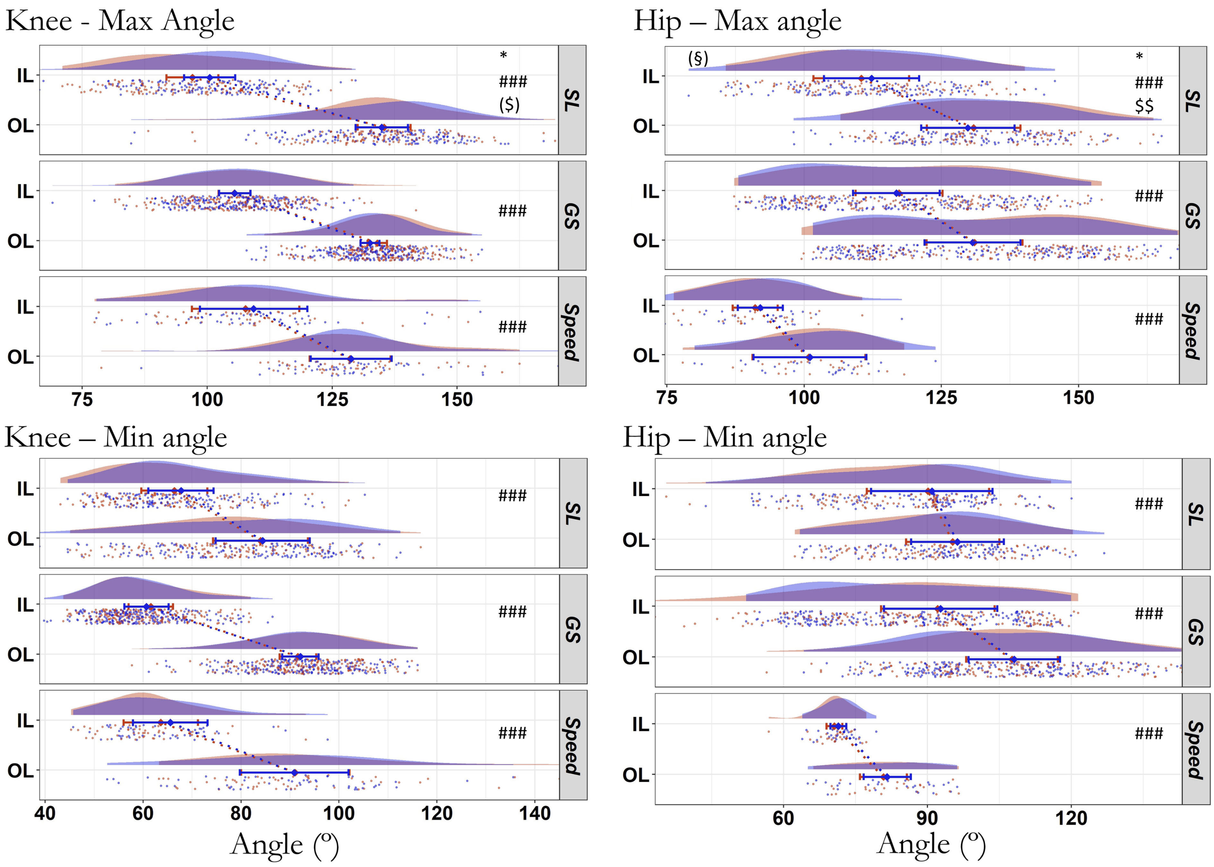

FIGURE 6
Minimal and maximal angle of the knee and hip during the first (blue) and last (red) run across all skier-sessions ($n = 39$). Values in degrees for the inside (IL) and outside (OL) leg. SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill. #Difference between IL and OL, *difference between first and last run, $ interaction effect, § *Post hoc* of the interaction showing the difference between first and last run on a single leg. ### $p < 0.001$; $$ $p < 0.01$; * $p < 0.05$; ($), (§) $p < 0.10$. The raincloud plot visualizes raw data (one point per right and left turn, i.e., inside and outside leg, respectively), probability density (cloud), and key summary statistics of the mean ± 95% confidence intervals. Each skier-session counts a certain number of turns (right turn, inside leg; left turn, outside leg) composing run one and four. Each individual dot represents the value of the variable for a given right and left turn (inside and outside leg, respectively). The dotted line in blue and red between the two rainclouds of each discipline's subplot links the inside and outside legs of the first and last run, respectively.

possible EMG activity increase due to inter-run effect. Indeed, the average vibration intensities decreased by a factor of 2–3 as the snow turned from hard frozen to soft in experienced skiers performing 24 runs, concomitantly with a substantial decrease in the EMG activity of the thigh muscles (Federolf et al., 2009). In any case, those changes were minor when considering the repeatability between two runs (first and fourth) with a CV_{intra} of 0.6% for RMS (averaged across five muscles and three disciplines, Appendices 1, 2) as elite skiers appear to maintain a stable neuromuscular activity across four runs.

Performance, kinematic, and technical parameters

The elite skiers participating in this study were able to maintain their performance (turn time and run time) across the four runs investigated (Table 5). Remarkably, elite skiers maintained their performance despite eventual changes in track conditions. While the snow surface was generally very hard (Table 1), in reality it is never perfectly rigid. The exact nature of the local snow surface was not precisely assessed and could progressively change with each racer as the snow is scraped and deformed (Reid et al., 2020). A recent kinematic study highlighted the role played by the ski shovel in groove formation during SL carved turns in elite skiers, as the ski continues to penetrate deeper into the snow with each subsequent run (Reid et al., 2020). During smooth carved turns, dynamical effects of the skis such as vibration and body-generated forces by the skier are negligible; but when skiing takes place on a varying terrain with rough and rippled snow surface, vibrational effects likely impact the ski-snow contact pressure (Heinrich et al., 2010). Overall, a combination of sufficient recovery time along proper track

TABLE 6 Comparison of first and last run for joint kinematics parameters.

Variable	Discipline	Signal	P value			Effect size		*Emmean diff.* Last-First [95%CI]	
			Run	Leg	Run*Leg	ICC_{adj}	ICC_{cond}	OL	IL
Min angle (°)	SL	HR	0.283	**0.000**	0.670	1.000	0.583	−1 [−2.9; 0.9]	−0.8 [−3.2; 1.6]
		KR	0.588	**0.000**	0.715	0.999	0.323	−0.4 [−2.8; 1.9]	−1.4 [−3.4; 0.7]
	GS	HR	0.856	**0.000**	0.400	1.000	0.232	−0.5 [−2.3; 1.3]	−0.6 [−1.9; 0.7]
		KR	0.490	**0.000**	0.956	0.998	0.027	−0.5 [−2.3; 1.3]	0.9 [−0.3; 2.1]
	Speed	HR	0.596	**0.000**	0.955	0.994	0.038	−0.8 [−5.2; 3.7]	−0.9 [−2.9; 1.2]
		KR	0.257	**0.000**	0.459	0.999	0.109	0.2 [−5.2; 5.6]	−1.9 [−4.7; 0.8]
Max angle (°)	SL	HR	**0.024**	**0.000**	**0.007**	0.661	0.427	1.1 [−1; 3.1]	−1.9 [−3.8; 0.1]
		KR	**0.015**	**0.000**	***0.052***	0.311	0.100	0.4 [−2; 2.9]	−3.4 [−5.8; −1]
	GS	HR	0.785	**0.000**	0.785	0.789	0.682	0.4 [−1.3; 2]	0.5 [−1.1; 2.1]
		KR	0.941	**0.000**	0.264	0.161	0.049	1.5 [0; 2.9]	−0.1 [−1.7; 1.5]
	Speed	HR	0.684	**0.000**	0.823	0.218	0.169	−0.2 [−4.6; 4.2]	−0.9 [−5.7; 3.9]
		KR	0.438	**0.000**	0.651	0.497	0.341	−0.2 [−4.2; 3.8]	−1.6 [−5.9; 2.7]
AV max flexion ($°.s^{-1}$)	SL	HR	0.482	**0.000**	0.651	1.000	0.675	11.5 [0.7; 22.2]	1.9 [−9.9; 13.6]
		KR	0.653	**0.000**	0.147	1.000	0.631	17.1 [3.4; 30.8]	2.1 [−10.7; 15]
	GS	HR	0.734	0.732	0.522	0.999	0.974	2.5 [−2.7; 7.8]	4.3 [−0.7; 9.3]
		KR	0.596	0.833	0.263	0.999	0.959	4.5 [−3.6; 12.6]	−2.6 [−9.3; 4.1]
	Speed	HR	0.722	0.983	0.645	0.994	0.978	1 [−4.3; 6.3]	−1.1 [−9.7; 7.6]
		KR	0.753	0.273	0.440	0.998	0.747	6.8 [−1.6; 15.1]	1.4 [−7.3; 10.2]
AV max extension ($°.s^{-1}$)	SL	HR	**0.025**	**0.000**	0.436	1.000	0.518	22.1 [8.4; 35.8]	11.2 [0.4; 22]
		KR	**0.008**	**0.000**	0.987	1.000	0.174	12.8 [−2.5; 28]	15.2 [4; 26.5]
	GS	HR	0.898	0.916	0.939	0.999	0.999	−0.7 [−6.9; 5.6]	2.2 [−3.5; 7.8]
		KR	0.141	***0.080***	0.890	0.999	0.873	4.8 [−3.1; 12.7]	4.6 [−1.7; 10.8]
	Speed	HR	0.700	0.507	0.829	0.998	0.986	−0.1 [−5.9; 5.7]	−1.6 [−8.9; 5.6]
		KR	0.640	0.190	0.607	0.999	0.861	−1.4 [−10; 7.3]	2.3 [−10; 14.5]
Amplitude (°)	SL	HR	0.106	-	-	0.560	0.560	2.6 [−0.6; 5.8]	
		KR	0.379	-	-	0.280	0.280	1.7 [−2.9; 6.3]	
	GS	HR	0.963	-	-	0.620	0.620	0 [−2.2; 2.1]	
		KR	0.402	-	-	0.390	0.390	0.8 [−1.1; 2.7]	
	Speed	HR	0.663	-	-	0.200	0.200	0.9 [−3.4; 5.2]	
		KR	0.417	-	-	0.050	0.050	2.2 [−3.2; 7.7]	

AV, angular velocity; KR, right knee; HR, right hip; OL, outside leg; IL, inside leg; SL, Slalom; GS, Giant Slalom; Speed, Super Giant Slalom and Downhill; MPF, mean power frequency; ICC_{adj}, adjusted intraclass correlation coefficient; ICC_{cond}, conditional intraclass correlation coefficient; Emmean diff.: estimated marginal mean of the difference between the last and first run. See Appendix 1 for detailed R squared values and coefficients of variation. Significant p-values ($p < 0.05$) are indicated in bold, trend ($0.05 \leq p \leq 0.01$) in italic and bold.

and skis preparation would allow elite skiers to maintain their performance for at least four runs during a regular racing training session.

The data from this study showed no measurable adjustments in the amplitude of movement, minimum angle and peak eccentric angular velocity between the first and fourth run in elite skiers (Figures 5–7). Indeed, the raincloud representation of the values showed a close overlap of the first and fourth run data (Figure 5). The absence of modification in flexion velocity suggests that elite skiers were able to maintain their ability to decelerate the downward movement and thus their capacity to resist the gravity and centrifugal force during the carved turn.

There was no change in the maximal angle (Figure 6) except in SL for the knee joint only, where a strong main effect of run was seen with a decrease on IL (−3.4°) and negligible increase on OL (<1°). The *post hoc* test of the interaction leg*run on the hip did not reach significance. Additionally, the peak extension angular velocity was not affected by runs repetition in Speed and GS. The SL was the only discipline showing some kinematic alterations with runs repetition, albeit the magnitude of change remained small (Figures 6, 7): the decrease (∼-3°) of the knee maximal angle on the IL and faster (∼+11–22° s^{-1}) knee and hip peak extension velocities are hardly visible to the naked eye. In the absence of clear concomitant EMG

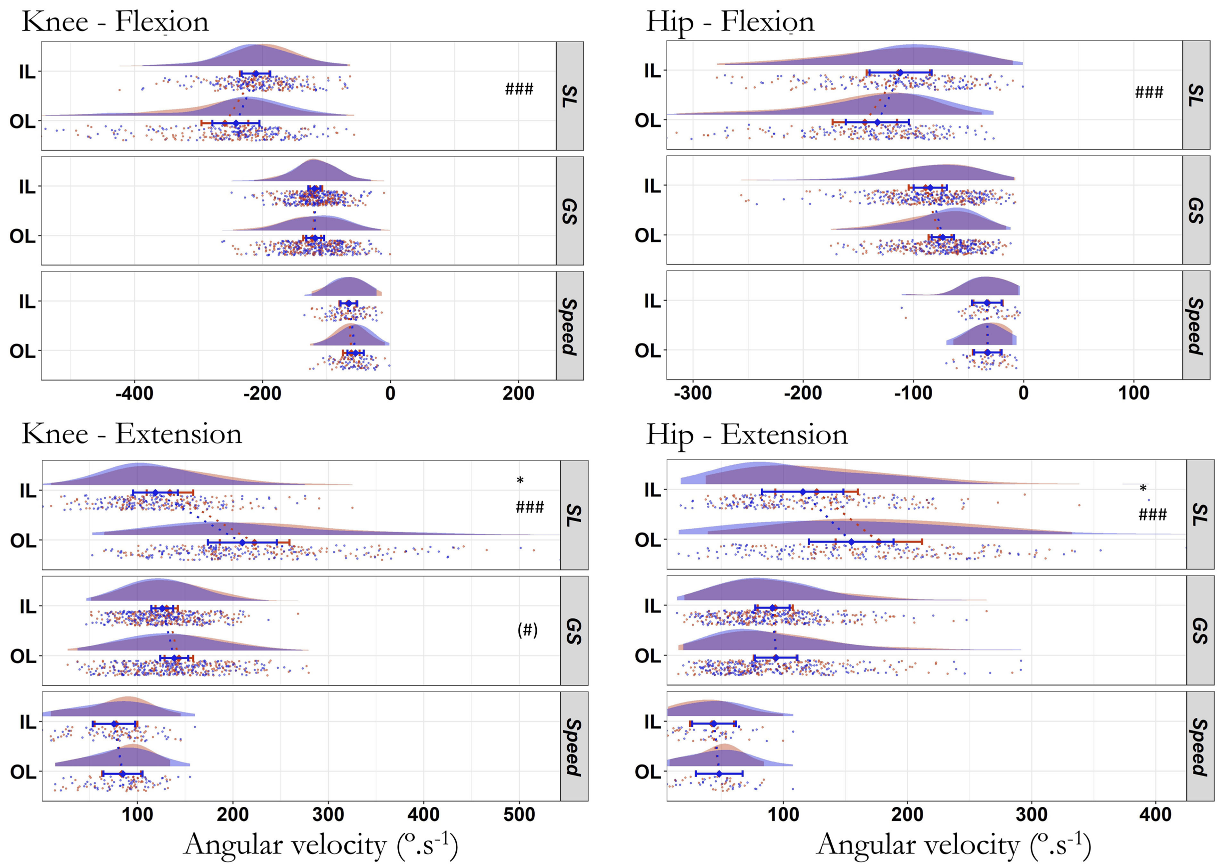

FIGURE 7
Peak angular velocity of the knee and hip during the first (blue) and last (red) run across all skier-sessions (n = 39). Values in degrees per second for the inside (IL) and outside (OL) leg. Due to the similarities between both *vastii*, only the medial head is represented. SL: Slalom, GS: Giant Slalom, Speed: Super Giant Slalom and Downhill. #Difference between IL and OL, *difference between first and last run. ### $p < 0.001$, * $p < 0.05$, (#) $p < 0.10$. A negative angular velocity indicates a knee/hip flexion. The raincloud plot visualizes raw data (one point per right and left turn, i.e., inside or outside leg, respectively), probability density (cloud), and key summary statistics of the mean ± 95% confidence intervals. Each skier-session counts a certain number of turns (right turn, inside leg; left turn, outside leg) composing run one and four. Each individual dot represents the value of the variable for a given right and left turn (inside or outside leg, respectively). The dotted line in blue and red between the two rainclouds of each discipline's subplot links the inside and outside legs of the first and last run, respectively.

changes, the small increase of peak extension angular velocity for hip and knee on both legs in SL (Figure 7) could be attributed to external factors such as the ski-snow interaction. These results showed that elite skiers are able to maintain similar kinematic characteristics while repeating runs. Stability of the kinematic pattern in elite skier is further confirmed in this study by a low intra skier-session (CV_{intra} ranging from 0.1 to 9.1%) and between skier-sessions (CV_{random} ranging from 1.4 to 12.8%) variability (Appendix 1). The total variability depended on the disparities between the skier-sessions and showed the good reproducibility of the measurement system as well as a homogenous level and steady technique in elite skiers. Compared to their intermediate counterparts, highly skilled skiers can reproduce the same motion pattern with accuracy (Müller et al., 1998). Of note, previous observations (Kiryu et al., 2011) also showed the adoption of a more upright posture in intermediate but not experienced skiers in a trial (5-min skiing demonstration for 4,000 m) and after repeated alpine ski turns. From a practical point of view, the high stability in performance and kinematic parameters in elite skiers suggests that future scientific studies or equipment testing could be done on a limited number of runs in this specific population.

Limitations of a field study

This study results should be considered specific to the number of runs, the duration of the work periods, as well as the duration and nature (active *vs.* passive) of the recovery pattern in-between. While the results from this study showed that elite skiers could maintain their performance during four runs, an inter-run effect with less stable neuromuscular pattern could have presumably been observed with additional and/or longer runs, as shorter recovery periods are constrained by the necessity to take the chairlift. It should be acknowledged that the number of runs ($n = 4$) included in this study is in the low range of a typical training session, albeit representative of elite practice. The future reliability studies may provide a better understanding of the contributors to the performance stability in alpine skiing and form a basis of worthwhile improvements in conditioning. As visible on the rainclouds (Figures 3–7), there was also less turns in Speed than GS and SL, due to longer turn duration and fewer gates in the Speed disciplines (SL: 40–60, GS: 25–50, SG: 15–40, and DH: 15–35 turns/run) (Gilgien et al., 2018). Thus, SG and DH (similar training slope, too few runs per specialty) were merged. Nonetheless, even if both specialties are traditionally grouped as the Speed discipline (Neumayr et al., 2003; Cross et al., 2021a)), a separate analysis would be recommended in future studies due to distinct kinematic requirements (Alhammoud et al., 2020).

The session used for normalization procedure of EMG signal took place the day before the ski sessions and the electrodes' location was marked with an indelible marker (Rainoldi et al., 2001), as it was not logistically possible for the athletes to complete it on the same day. The reproducibility of isometric MVC performed in the same conditions between days was tested in a separate experiment and was interpreted as *high* or *very high* ($0.749 \leq$ ICCs ≤ 0.966). Furthermore, a high level of EMG measures repeatability between days was shown for quadriceps (ICC > 0.70) (Rainoldi et al., 2001) and hamstrings (ICC 0.70–0.89) (Bussey et al., 2018) with this procedure. Additionally, medial hamstrings (SM, ST) were not individualized as it was not possible to attribute the recorded EMG signal to one specific muscle (possible crosstalk effect) without ultrasound to precisely localize these two muscles. The strong passive vibrations, due to uneven surfaces and high speeds involved in alpine skiing, stimulate the muscle spindles and activate a larger number of motoneurons, which in turn elevates the EMG activity and can cause early onset of muscle fatigue (Shinohara, 2005). Filtering was therefore necessary to avoid the contamination of the signal due to vibrations that increase the EMG RMS during a given exercise (Borges et al., 2017). However, a small degree of muscle fatigue could have been masked by the vibration effect on EMG since the ski-snow interaction properties likely changed throughout a training session. Finally, the rotations occurring at the skier's hip joint due to counterrotation and dissociation (LeMaster, 2010) were neglected as the goniometer recorded two planes only. However, both wireless surface EMG electrodes and goniometers were selected to ensure that athletes performed at their peak without any disturbance while skiing to preserve measurement ecological validity (Berg et al., 1995; Kröll et al., 2010; Panizzolo et al., 2013).

Conclusion

The aim of this study was to characterize the EMG changes in response to repeating four competitive runs in elite skiers. There was an increase in RMS from the first to the fourth run for the *vastii* (on both legs for VL in Speed and VM in SL, VM in GS on OL). There was no meaningful main effect of run on EMG activation time or mean power frequency beyond the skier's variability. Performance, defined as run time and turn time, was not affected and there were no meaningful kinematic changes. As hypothesized, there were no clear adjustments suggesting neuromuscular alterations, and the changes observed could partly be attributed to inter-run variability, or changes in the ski-snow properties. Overall, neuromuscular activity remains highly stable from the first to the fourth run in elite skiers with low variability across runs repetition. This highlights the specificities of alpine skiing with the necessity to take the chairlift (passive recovery) between runs and the limited number of runs performed per session by elite skiers. Importantly, this study investigated the EMG changes within a training session in which the skiers were able to maintain their performance. Future studies should look at the fatigue responses to longer sessions or to repeated sessions on consecutive days.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the corresponding author, upon reasonable request.

Ethics statement

The studies involving human participants were reviewed and approved by University of Lyon. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MA and CAH conceived the study. MA and SR collected the data. MA, CH, and BM analyzed the data. MA, OG, and FM interpreted the data. MA drafted the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.829195/full#supplementary-material

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Heel riser height and slope gradient influence the kinematics and kinetics of ski mountaineering—A laboratory study

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In ski mountaineering, equipment and its interaction with the exercising human plays an important role. The binding, as the crucial connection between boot and ski, must ensure safe fixation during downhill skiing and a free moving heel when walking uphill. Uphill, the binding offers the possibility to adopt the height of the heel (riser height) to personal preferences and the steepness of the ascent. This possible adjustment and its influence on various biomechanical parameters are the focus of this work. For this study, 19 male leisure ski mountaineers were tested on a treadmill, ascending at a fixed submaximal speed (3.9 ± 0.4 km·h^{-1}) at 8, 16, and 24% gradient and with three heel riser heights, low (0 cm), medium (3.0 cm) and high (5.3 cm). The applied biomechanical measurement systems included a 3D motion capture system in sagittal plane, pressure insoles, a with strain gauges instrumented pole, spirometry and a comfort scale. Step length and step frequency were influenced by the riser height and the gradient ($p \leq 0.001$). The high riser height decreased the step length by 5% compared to the low riser height over all tested gradients, while steps were 9.2% longer at the 24% gradient compared to the 8% gradient over all three riser heights. The high riser height revealed a force impulse of the pole 13% lower than using the low riser height ($p < 0.001$). Additionally, the high riser height reduced the range of motion of the knee joint and the ankle joint compared to the low riser height ($p < 0.001$). Therefore, advantageous settings can be derived, with the low riser height creating proper range of motion for ankle, knee and hip joint and higher propulsion via the pole at 8%, while higher riser heights like the medium setting do so at steeper gradients. These findings are in line with the conducted comfort scale. We would not recommend the highest riser height for the analyzed gradients in this study, but it might be an appropriate choice for higher gradients.

KEYWORDS

human-equipment interaction, sports equipment, treadmill ergometry, winter sports, ski mountaineering, mechanical efficiency

Introduction

Most sports are highly reliant on the equipment used in performing them. Applying the proper equipment can promote the progression of performance (Haake, 2009) and minimize the risk of injuries (Stefanyshyn and Wannop, 2015). These factors are directed by sport-specific rulebooks to ensure safe and attractive competition circumstances (Cooper and De Luigi, 2014; Müller et al., 2016; Crouch et al., 2017). However, human–equipment interaction is not trivial and can be affected by various parameters (Stefanyshyn and Wannop, 2015).

To serve changing demands, some sports offer the possibility to adapt the equipment, even during exercise. One of these sports is ski mountaineering (skimo). To serve the demands of walking uphill and skiing downhill, the boots, binding and skis have specific features. For example, the heel binding enables the user to alter a heel riser height according to personal preferences in the given environment when walking uphill. General recommendations indicate using a higher riser height at steeper slope gradients to keep the foot in a more horizontal position when walking uphill to sustain an upright posture and reduce the stretch to the calves (Vives, 1999; Winter, 2001). A common exception are race bindings which do not provide possibilities for changes in riser height. These bindings offer one fixed height, which is comparable to a medium riser height in touring or recreational bindings (House et al., 2019) and is used universally in flat, but also steep terrain.

Nevertheless, the justification to various recommendations for skimo riser height is more reliant on experts' opinions and general experience than on empirical evidence. Scientifically, skimo is a rather young sport with only a few topic areas thoroughly researched. Skimo racing has been shown to be one of the most strenuous endurance exercises at the elite level (Duc et al., 2011; Praz et al., 2014; Fornasiero et al., 2018; Gaston et al., 2019; Lasshofer et al., 2021). Part of the performance improvement aspect is the enormous development in training and equipment over the last decades (Bortolan et al., 2021), halving the metabolic cost of moving with skis on snow (Formenti et al., 2005). To reach a summit, steeper slope angles provide lower vertical energy cost and are therefore mechanically more efficient, compared to flatter slope angles. While walking speed does not influence the vertical energy cost in slightly inclined terrain, maintaining higher speed in steep terrain is associated with lower vertical energy cost (Praz et al., 2016a,b). Movement patterns are highly influenced by terrain, therefore the foot sole loading pattern clearly distinguishes between a direct ascent and traversing (Haselbacher et al., 2014). The combined effects of equipment and equipment variations in skimo have not been studied in depth. Tosi et al. (2009) observed only a small influence of adding weight to the ankle concerning energy cost. Adding one percent of body weight to the ankle during skiing only resulted in an increase of energy cost by 1.7%.

TABLE 1 Age, anthropometrics, equipment and training.

	Overall ($n = 19$)		
	Mean ± SD	**Min**	**Max**
Age [yr]	34.0 ± 7.3	21	49
Body height [cm]	179.5 ± 8.7	159	195
Body mass [kg]	78.0 ± 8.3	58.5	94.8
BMI [kg·(m^2)$^{-1}$]	24.3 ± 2.9	18.1	30.9
VO_{2peak} [ml·min^{-1}·kg^{-1}]	57.1 ± 5.8	48.1	65.8
Ski length [cm]	172 ± 8	160	188
Ski length in % of body height [%]	96 ± 5.4	87.7	103.9
Ski width [mm]	84 ± 13	60	106
Pole length [cm]	129 ± 6	120	145
Pole length in % of body height [%]	72.2 ± 2.7	68.4	78.6
Total training volume [h/week]	8.3 ± 4.3	2	20
Skitours [n/month]	9.4 ± 5.6	2	20
Elevation gain [m/tour]	1,076 ± 224	750	1,500

SD, standard deviation; BMI, body mass index.

The present study was designed to extend the knowledge on the biomechanics of skimo, verify the experience-based opinions and provide further understanding of human–equipment interaction in this sport.

Therefore, the goal of this study was to compare the influence of different heel riser heights and gradients on kinematic, kinetic variables, mechanical efficiency and comfort during treadmill skimo. We hypothesize that higher riser heights are beneficial on steeper slope gradients (e.g., longer step cycle, more horizontal foot position, more upright body position, pole application) and low riser heights on low slope gradients.

Methods

Participants and protocol

As inclusion criteria, participants were male, between 18 and 50 years old, practice skimo regularly, do not participate in skimo races and apply different available riser heights regularly while walking uphill. Nineteen participants were included in the study, whose anthropometric data, equipment characteristics and training habits are shown in Table 1. All participants took part voluntarily and signed a letter of agreement. The study was approved by the ethical committee of the University of Salzburg (EK-GZ: 36/2018).

Participants walked on a h/p/cosmos Saturn treadmill (h/p/cosmos sports medical GmbH, Germany, size 300 × 125 cm) for two sessions using standardized skimo equipment. An Atomic Backland Tour binding was mounted on a 170 cm long Atomic Backland 78 ski (Atomic Austria GmbH, Austria). Atomic Backland Sport boots (Atomic Austria GmbH, Austria) in various sizes with a reported range of motion of 74° were used for all tests (Atomic, 2021). Short standard skimo climbing skins (0.3 m) were mounted below the area of the binding to ensure sufficient grip but not to fully restrict gliding, which then provided a perception similar to walking on snow. Instrumented poles, in which the lengths were individually adjusted to fit the participants' habitual pole length, were used for the two measurement sessions. The first test was a skimo specific performance test to determine physiological fitness, determine the walking speed for the second session and to become familiar with the movement characteristics on the treadmill. This test was a combination of an incremental test at a 16% gradient (0.4 km·h^{-1} increment every 4 min with a 30 s break to take the lactate sample starting at 2.6 km·h^{-1} until reaching ≥4 mmol·L^{-1} blood lactate) and after a passive 3-min break, a ramp test at 24% gradient (0.4 km·h^{-1} increment every minute starting at 2.6 km·h^{-1} until reaching exhaustion). The second session was a duration test, which had to be at minimum 72 h and at maximum 2 weeks after the first session. The walking speed, which was on average 4.0 ± 0.5 km·h^{-1}, was derived from the first session and corresponds to the speed at 1.5 mmol·L^{-1} blood lactate. The testing included three times 15 min at 8, 16, and 24% gradient in this order at the given consistent speed, while each block was split in three times 5 min intervals at the three available riser heights being applied randomly. The break between the 5 min intervals was 1 min to change the riser height, and between different gradients a break of 2 min was necessary to change the gradient and the riser height. The characteristics of the riser height were low (0.0 cm), medium (3.0 cm), and high (5.3 cm) (Figure 1). Only the last minute of each 5 min interval was recorded and the middle 20 strides out of this minute were further analyzed.

FIGURE 1
Showing the used skimo binding with the medium riser height applied. By flipping the support area the low or high riser height could be applied. © 2020 | Atomic Austria GmbH.

Measuring setup

Participants were equipped with three different biomechanical systems. The Moticon sensor insoles (Moticon ReGo AG, Germany) recording at 100 Hz with an integrated 3+3-axis IMU were used to measure foot pressure distribution perpendicular to the insole, apparent as vertical ground reaction force. Gait and foot sole loading patterns were computed with the Moticon Science software. The software creates an automated report over selected steps including step frequency, step length along the surface, timing parameters (cycle, step, single stance, double stance and swing time) force and pressure parameters. To do so, the input parameters are total force, pressure distribution and acceleration along the x-axis. Maximum ground reaction force data were intercepted in F_{peak} and F_{max}, where F_{peak} was the peak value at initial ground contact and F_{max} the overall maximum value typically occurring during push off. The force impulse was calculated by multiplying contact time with the mean force during ground contact.

An in-house built instrumented pole (University of Salzburg, Austria) with a strain gauge force transducer (ME-Meßsysteme GmbH, Hennigsdorf, Germany) was used for measuring pole forces directed along the pole. Sampling frequency for this system was 200 Hz and data was transmitted wirelessly via Bluetooth to a Smartphone application (Sentax, Sweden). A 12 Hz second order low pass Butterworth filter was applied to the raw data before further data processing and obtaining pole ground contact time, mean and maximum ground reaction force.

Kinematic data was captured by a Qualisys Miqus 3D motion capture system recording at 100 Hz (Qualisys AB, Sweden). The system was applied to assess data in sagittal plane. Markers were placed on the boot (toe, heel and ankle), knee (lateral joint line), hip (greater trochanter), and shoulder (acromion) of the participants. Boot markers represented the foot, but did not necessarily correspond with anatomical structures or provide the same possibility to move because of the rigidity of the boot shell. The ankle marker was placed at the pivot point of the boot and the criterion for the heel and toe marker were to be at the same height measured from the ground. Additionally, two markers were placed on the pole tube, 20 cm and 35 cm above the pole tip. Joint angles were defined based on the following marker positions: Ankle angle: angle between toe marker, ankle marker and knee marker; Knee angle: angle between ankle marker, knee marker and greater trochanter marker; Hip angle: angle between knee marker, hip marker and shoulder marker. The ROM (range of motion) was calculated as the difference between maximum and minimum joint angle during each analyzed cycle. The pole angle was measured as the angle between the pole and the treadmill at initial contact of the pole. The torso angle, defined as the angle in sagittal plane between a horizontal line and the line between the shoulder marker and the hip marker, and the distance between hip and toe were captured during initial contact of the foot. The distance between hip and toe assesses the hip's horizontal distance relative to the toe, which corresponded to the pivot point of the binding. The foot angle, defined as the angle in sagittal plane between the horizontal axis and the line between the toe and heel marker, described the foot position during ground contact relative to horizontal. When applying the lowest riser height setting, respectively, no riser height, the line between the two relevant markers was parallel to the surface. Negative values indicate that the heel marker was on a lower level than the toe marker in the global space, while positive values indicate that the heel marker was higher than the toe marker. Since the 3D motion capture system was applied unilaterally, foot forces and pole forces were also analyzed unilaterally. Assuming skimo being a cyclical movement, minor right-left asymmetries were expected to be neutralized over the tested cohort and therefore no loss of data quality was presumed.

A portable metabolic system, a Cosmed K5 (Cosmed, Rome Italy) was applied in breath-by-breath mode to measure oxygen uptake. Metabolic rate was taken from the Cosmed data output as well. The system was calibrated before each test following the instruction manual, the facemasks were fitted properly and a fan in combination with opened windows ensured fresh air circulation. Skimo specific maximum oxygen consumption was defined as a mean value over 15 consecutive breaths at the end of the ramp protocol with a flattening VO_2 slope and respiratory exchange ratio being > 1.05 or rating of perceived exertion (Borg 6–20) being > 18. Lactate samples were taken by qualified researchers from an ear lobe before, during and after the test and the 20 μl blood sample was analyzed by an EKF-Diagnostics Biosen C-line system (EKF-diagnostic GmbH, Germany).

Mechanical efficiency was calculated similar to Praz et al. (2014, 2016a,b):

$$Mechanical\ efficiency = vertical\ mechanical\ power / metabolic\ rate$$

Where vertical mechanical power followed the equation:

$$Vertical\ mechanical\ power = m^{*} g^{*} sin(arctan(\theta))^{*}\ v$$

with m being the mass of the athlete + the equipment, g the acceleration of gravity, θ the gradient given in % and v the walking velocity ($m \cdot s^{-1}$).

Additionally, after each condition participants were asked how comfortable the applied riser height was. For this purpose, a comfort scale (1–10) was used, with 1 representing a very uncomfortable situation and 10 representing a very comfortable situation.

Statistics

For statistical calculations, SPSS Version 27 (IBM Cooperation, USA) was used. A multifactorial ANOVA with repeated measurements was applied for determination of main effects of gradient and riser height, while a one-way ANOVA was used for detailed analysis within the separate gradients. For pairwise comparisons, a Bonferroni correction was applied. Whenever sphericity was not given (Mauchly Test $p < 0.05$), Greenhouse-Geisser correction was applied for within-subjects effects. Alpha value for significance was defined as < 0.05. Partial Eta squared (eta_p^2) is reported as effect size.

Results

Only complete datasets were analyzed for each dependent variable, which resulted in a sample size of 18 for the kinematic parameters and foot pressure and 16 for parameters related to the instrumented pole. The loss of data in one case was due to fatigue and incomprehensible technical issues leading to lost data in the other cases.

Table 2 summarizes kinematic and kinetic parameters, mechanical efficiency and comfort scale for each situation (three riser heights for each of the three slope gradients) including the main effects and interaction effects.

Cycle characteristics

Both, step length and step frequency revealed a main effect of gradient and riser height (both, $p < 0.001$) without an interaction effect (Figures 2, 3). On average over all gradients, step length decreased by 5% from low to high riser height. On average over all riser heights, step length increased by 9.2% from 8% gradient to 24% gradient. In contrast to step length, step frequency was increased by 4.8% from low to high riser height and was reduced by 5.4% from 8% gradient to 24% gradient.

The overall reduction of cycle time by 4% from low to high riser height over all gradients ($p < 0.001$) is a result of the reduction of step duration (−3.7%; $p < 0.001$) and swing duration (−5.5%; $p = < 0.001$). No interaction effects were found for cycle timing characteristics.

Leg and pole characteristics

The force impulse of the foot (Figure 4) showed neither an effect of gradient ($p = 0.498$) or riser height ($p = 0.05$), nor an

TABLE 2 Kinematic and kinetic data.

					ANOVA (p-value/eta$_p^2$)		
		low RH	med RH	high RH	GR	RH	GR*RH
Distance trochanter—toe [m]	8%	0.51 ± 0.05	0.48 ± 0.05	0.45 ± 0.07			
	16%	0.56 ± 0.05	0.54 ± 0.06	0.52 ± 0.06	**<0.001/0.94**	**<0.001/0.75**	**0.003/0.23**
	24%	0.59 ± 0.05	0.57 ± 0.06	0.55 ± 0.06			
Torso angle [°]	8%	86 ± 5	87 ± 5	87 ± 4			
	16%	82 ± 5	83 ± 5	84 ± 5	**<0.001/0.83**	**<0.001/0.79**	**<0.001/0.32**
	24%	76 ± 7	78 ± 7	79 ± 6			
Pole angle [°]	8%	68 ± 5	69 ± 7	69 ± 6			
	16%	66 ± 6	66 ± 7	66 ± 7	**<0.001/0.71**	0.07/0.14	**0.036/0.14**
	24%	61 ± 6	62 ± 7	63 ± 7			
Pole contact time [s]	8%	0.68 ± 0.09	0.68 ± 0.09	0.67 ± 0.08			
	16%	0.75 ± 0.1	0.74 ± 0.1	0.7 ± 0.1	**<0.001/0.86**	**<0.001/0.68**	**0.005/0.23**
	24%	0.82 ± 0.09	0.77 ± 0.09	0.77 ± 0.1			
Pole Fmax [N]	8%	43 ± 12	42 ± 11	44 ± 11			
	16%	55 ± 15	52 ± 14	52 ± 13	**<0.001/0.85**	**0.005/0.31**	0.072/0.14
	24%	71 ± 17	66 ± 15	65 ± 15			
Sole Fmax [N]	8%	936 ± 126	898 ± 126	886 ± 131			
	16%	968 ± 142	939 ± 134	913 ± 148	**0.001/0.43**	**<0.001/0.48**	0.606/0.04
	24%	984 ± 112	973 ± 135	951 ± 138			
Sole Fpeak [N]	8%	595 ± 108	642 ± 129	680 ± 140			
	16%	583 ± 116	622 ± 95	645 ± 104	0.292/0.07	**<0.001/0.64**	0.309/0.07
	24%	562 ± 96	648 ± 137	641 ± 108			
Cycle time [s]	8%	1.32 ± 0.12	1.28 ± 0.11	1.26 ± 0.13			
	16%	1.37 ± 0.12	1.34 ± 0.13	1.31 ± 0.13	**<0.001/0.48**	**<0.001/0.68**	0.547/0.04
	24%	1.38 ± 0.13	1.35 ± 0.12	1.34 ± 0.13			
Step time [s]	8%	0.79 ± 0.08	0.78 ± 0.07	0.77 ± 0.09			
	16%	0.82 ± 0.07	0.8 ± 0.07	0.78 ± 0.08	**0.016/0.26**	**<0.001/0.37**	0.579/0.04
	24%	0.83 ± 0.07	0.81 ± 0.07	0.8 ± 0.08			
Single stance time [s]	8%	0.66 ± 0.06	0.64 ± 0.06	0.63 ± 0.08			
	16%	0.68 ± 0.06	0.67 ± 0.07	0.65 ± 0.07	**0.002/0.36**	**<0.001/0.61**	0.651/0.03
	24%	0.69 ± 0.06	0.67 ± 0.06	0.66 ± 0.06			
Double stance time [s]	8%	0.13 ± 0.02	0.14 ± 0.02	0.14 ± 0.03			
	16%	0.14 ± 0.03	0.13 ± 0.02	0.13 ± 0.03	0.289/0.07	0.947/<0.01	0.327/0.07
	24%	0.14 ± 0.03	0.14 ± 0.03	0.14 ± 0.03			
Swing time [s]	8%	0.53 ± 0.05	0.5 ± 0.06	0.48 ± 0.06			
	16%	0.55 ± 0.06	0.54 ± 0.06	0.53 ± 0.06	**<0.001/0.53**	**<0.001/0.63**	0.09/0.11
	24%	0.55 ± 0.06	0.54 ± 0.06	0.53 ± 0.06			
Foot angle [°]	8%	−4.5 ± 0.5	4.1 ± 0.6	8.4 ± 0.8			
	16%	−9.2 ± 0.5	−0.6 ± 0.6	3.7 ± 0.8	**<0.001/1**	**<0.001/0.99**	0.153/0.1
	24%	−13.5 ± 0.5	−5 ± 0.6	−0.7 ± 0.8			
Mechanical efficiency	8%	0.1 ± 0.01	0.09 ± 0.01	0.09 ± 0.01			
	16%	0.14 ± 0.01	0.14 ± 0.01	0.14 ± 0.02	**<0.001/0.98**	0.756/0.02	0.186/0.09
	24%	0.17 ± 0.02	0.17 ± 0.02	0.17 ± 0.02			
Comfort (1–10)	8%	8.6 ± 1.3	7.0 ± 1.7	4.8 ± 2.6			
	16%	6.6 ± 2.0	7.5 ± 1.5	6.6 ± 1.8	**0.016/0.24**	**<0.001/0.41**	**<0.001/0.41**
	24%	5.2 ± 1.9	6.5 ± 2.2	6.1 ± 2.1			

Mean ± standard deviation; RH, riser height; GR, gradient; GR × RH = interaction effect between gradient and riser height. Significant results are presented in bold.

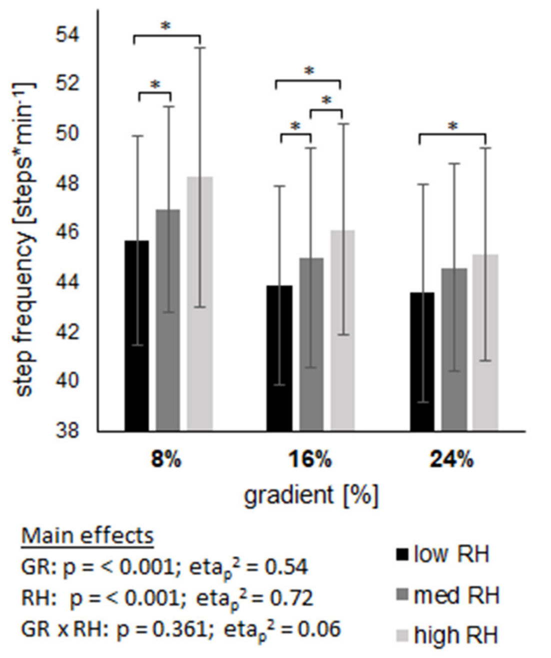

FIGURE 2
Shows the step frequency across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect. The asterix (*) labels pairwise comparisons within each grade, with the level of significance (p) set at <0.05.

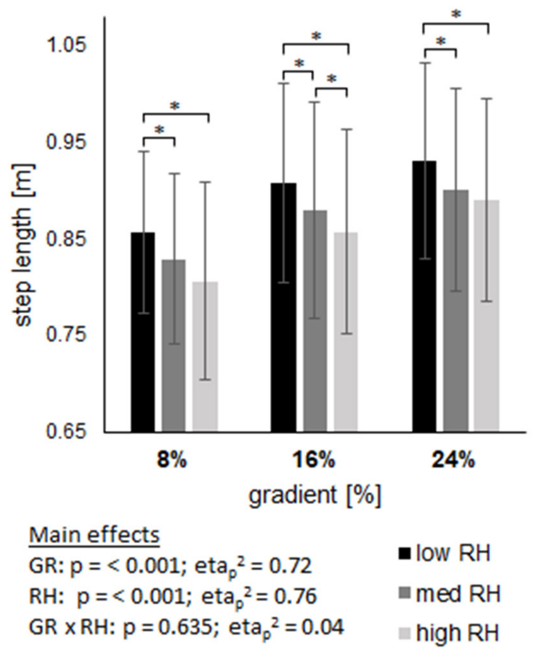

FIGURE 3
Shows the step length across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect. The asterix (*) labels pairwise comparisons within each grade, with the level of significance (p) set at <0.05.

interaction effect of these two variables ($p = 0.73$). However, the almost significant mean change of the force impulse from low to high riser height over all gradients was −4%, revealing its relevance with a large effect ($eta_p^2 = 0.16$). Maximum foot force was affected by gradient ($p = 0.001$) and riser height ($p < 0.001$), showing an increase from 8 to 24% gradient and a decrease from low to high riser height. Peak foot force revealed no effect for gradient ($p = 0.292$), but for riser height ($p < 0.001$), showing an increase from low to high riser height. No interaction was found for maximum and peak foot force ($p = 0.606$; $p = 0.309$).

The force impulse of the pole (Figure 5) showed a main effect of gradient and riser height ($p < 0.001$) with an average increase from 8 to 24% gradient of 76.2%. The average decrease over all gradients from low to high riser height was −12.6%, being different within each gradient (−2.8% at 8%; −14.3% at 16%; −16.4% at 24%), resulting in an interaction effect of riser height and gradient (p = 0.001). The pole angle at initial contact was greater at 8% compared to 24% gradient ($p < 0.001$), but not affected by riser height, although a notable trend is apparent ($p = 0.07$; $eta_p^2 = 0.14$). The interaction of gradient and riser height ($p = 0.036$) showed an increase from low to high riser height at 8 and 24% gradient, but an unaffected situation at 16% gradient. Maximum pole force revealed a main effect of gradient ($p < 0.001$) and riser height ($p = 0.005$), but with no interaction effect ($p = 0.07$). The maximum force decreased by −4.7% from low to high riser height and increased by 59.6% from 8 to 24% gradient.

Mechanical efficiency revealed a main effect of the gradient ($p < 0.001$) increasing from 8% gradient up to 24% gradient, with no effect of riser height or an interaction effect.

Joint kinematics

The ROM of joint angles are displayed in Figures 6–8, with main effects of gradient and riser height ($p \leq 0.001$) on both, ankle and knee, while the ROM of the hip was only affected by riser height ($p < 0.001$) and not by gradient ($p = 0.27$). The high riser height reduced the ROM of ankle and knee joint compared to the low riser height, without an interaction effect (ankle $p = 0.931$; knee $p = 0.511$). The hip joint ROM revealed an interaction effect ($p < 0.001$) with an increase from low to high riser height at 8% gradient, in contrast to a decrease from low to high riser height at 16 and 24% gradient.

The foot angle is listed in Table 2, with main effects of gradient and riser height ($p < 0.001$) but no interaction effect ($p = 0.153$). Closely matching values and therefore identifiable pairs were found for (1) low riser height at 8% and medium riser height at 24%, (2) medium riser height at 8% and high riser

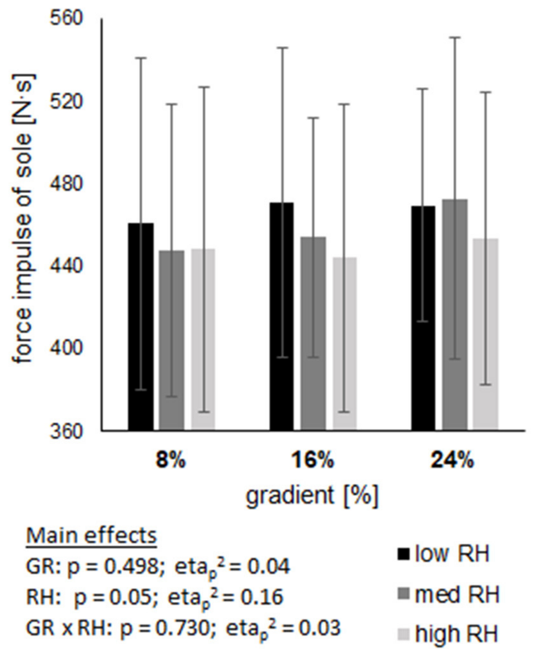

FIGURE 4
Shows the impulse of sole force across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect.

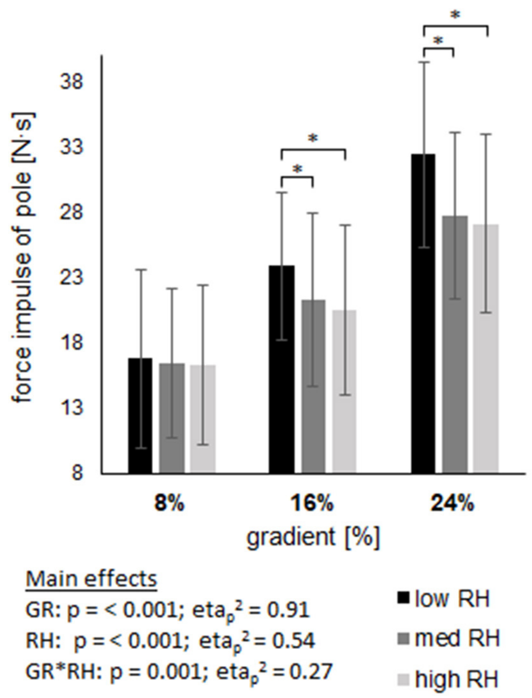

FIGURE 5
Shows the impulse of pole force across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect. The asterix (*) labels pairwise comparisons within each grade, with the level of significance (p) set at <0.05.

height at 16% and (3) medium riser height at 16% and high riser height at 24%.

Discussion

The goal of this study was to compare the influence of different riser heights and slope gradients on kinematics and kinetics during treadmill skimo. It was demonstrated that most of the parameters are influenced by both, gradient and riser height, which makes it necessary to discuss both influences and their interactions.

Gait characteristics are shown to be strongly influenced. Step frequency was increased by 5% from low up to high riser height independent of gradient and decreases by 5% from 8% gradient up to 24% gradient independent of the applied riser height. Step length data is in contrast to step frequency, since walking velocity was the same for all situations. It has also been shown in walking that the reduction of step frequency is dependent on slope gradient (Kawamura et al., 1991) and is concordant with the findings of Praz, Fasel (Praz et al., 2016a) in skimo. The change in step length is also visible in horizontal distance between the greater trochanter and the toe marker at initial contact, which describes step length in front of the body. Since the treadmill surface allows no gliding phase of the ski after initial contact, no change in step length is expected after initial contact. The fact that a higher riser height does not allow the athlete to drop the heel on the ski, restricts the ability to push the foot forward and increase ROM. This could also be discussed in relation to boot stiffness and ROM of the boot and the ankle joint, since both factors could enhance this effect. In this context we also need to differentiate between all-mountain equipment and racing equipment. While racing equipment is built to be as light as possible with little friction and resistance at the boots' pivot point at the ankle, all-mountain equipment targets other main objectives like thermo-insulation or comfort and has more resistance when rotating the boot's cuff. It might be inevitable to adopt the riser height with a stiff boot to compensate for the lack of boot flexibility.

The analysis of step length agrees with gait analysis, where the high riser height was shown to provide a shorter swing time and shorter single stance phase, reasoned by an earlier heel contact with the binding at foot strike. Additionally, ROM of the ankle and the knee were directly affected by the change in riser height. Figures 6, 7 show the reduction of the joints' ROM when using a higher riser height, independent of gradients. These interpretations are also supported by the ROM of the hip (see Figure 8) at 16 and 24% gradient, where a significantly lower

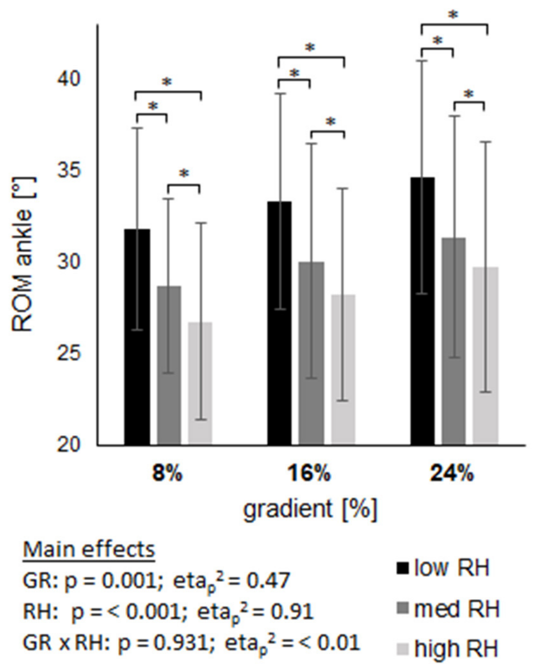

FIGURE 6
Shows the range of motion (ROM) of the ankle joint across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect. The asterix (*) labels pairwise comparisons within each grade, with the level of significance (p) set at <0.05.

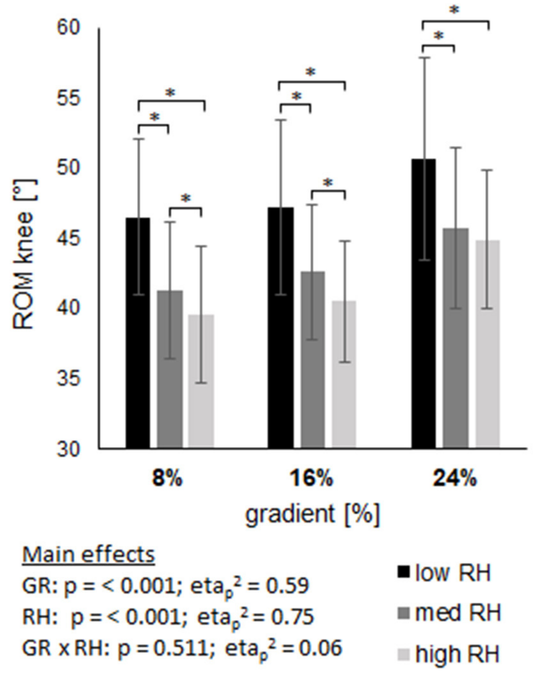

FIGURE 7
Shows the range of motion (ROM) of the knee joint across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect. The asterix (*) labels pairwise comparisons within each grade, with the level of significance (p) set at <0.05.

ROM when using the high riser height was found. The hip is not extended maximally because the heel is elevated during push off, which lowers the ROM of the hip and consequently step length as well. We interpret the evident interaction and inverse shape of hip ROM change at 8% gradient by a counterproductive limitation in ROM of the knee and ankle joint due to the high heel, which then is compensated by the hip. In general the boot is reported to have a ROM of 74°, while we found an average ankle ROM from 27 to 35° at various situations, which excludes the boot being a limiting factor concerning ankle movement.

These results, supported by the highest effects of riser height setting within gradients for step characteristics, trochanter to toe distance and gait analysis found at 8% gradient, lead to the conclusion that the movement pattern is influenced the most by the different riser heights at the lowest tested gradient. Additionally, the comfort scale clearly demonstrates the highest riser height being the most uncomfortable choice at 8% gradient.

Pole force application may also be more effective at the lower riser height. On one hand, impulse of pole forces and maximum pole forces were higher when using the low riser height compared to the high riser height. On the other hand, pole angles at initial contact of the pole were lower when using the low riser height, at 8 and 24% gradient. This combination of a more advantageous direction of force application, higher force values and higher force impulse indicate stronger propulsion. Nevertheless, a flatter pole angle is not only affected by riser height, but also by gradient. This reveals a more beneficial value in terms of propulsion at 24% compared to 8% gradient. The flatter pole angle at initial contact can be linked to a flatter torso angle occurring at steeper gradients. With these benefits occurring at 24%, it is an advantage to choose this gradient compared to lower gradients. This finding is in concordance with the vertical energy cost analysis of Praz et al. (2016a,b), who also suggested to choose a steeper gradient if possible.

In the analysis of foot pressure, it was necessary to analyze peak and maximal pressures separately. Peak force describes first peak in the gait cycle, as a result of initial contact, which is also known as braking force during running (Heiderscheit et al., 2011). Maximum pressure occurred typically during push off phase. Both events, initial contact and push off, were demonstrated to be influenced by riser height. Even though single values do not represent the course of the occurring force, they indicate a probable shift or a trend. Although we cannot address the overall braking or propulsive forces, peak values indicate higher peak braking force for the high riser height compared to the low riser height. This could be explained by

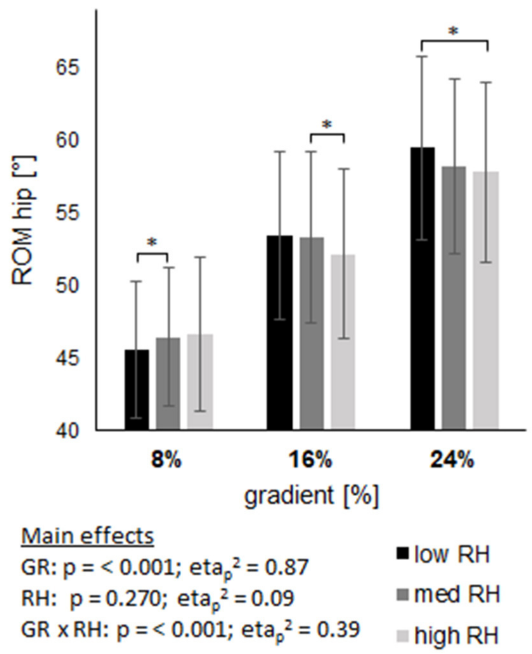

FIGURE 8
Shows the range of motion (ROM) of the hip joint across three gradients (GR), each including three riser heights (RH). Data are displayed as mean value ± standard deviation. GR × RH represents their interaction effect. The asterix (*) labels pairwise comparisons within each grade, with the level of significance (p) set at <0.05.

the fact that there was earlier heel contact when using the high riser height, which resulted in a higher force value. However, based on that, the direction of force was not measurable with the current setup, it is possible that the peak value, due to the forward inclined foot when using the high riser height, also creates a propulsive force. This would be comparable to the potential effect of heel to toe drop in running shoes (Richert et al., 2019; Mo et al., 2020).

It was demonstrated that foot angle is well comparable for certain combinations of gradient and riser height (8% low vs. 24% medium, or 8% medium vs. 16% high, or 16% medium vs. 24% high). While for example ankle ROM or cycle timing parameters show similar results for the mentioned pairs of a quasi-similar position of the foot in space, the analyzed force parameters do not necessarily confirm this similarity. Since the walking speed was the same for all situations, a higher strain existed for higher gradients and therefore similar kinematic parameters resulted in different kinetic measurements. Comfort scale could demonstrate the supremacy of the low riser height at 8% gradient and the medium riser height at 16 and 24% gradient, whereby a foot angle between −5° and 0° was proven to be the most comfortable choice.

As a link between biomechanical measurements and physiological responses, mechanical efficiency was calculated. Even though various biomechanical parameters showed an effect of the heel riser height, the mechanical efficiency was not affected. Nevertheless, mechanical efficiency was affected by gradient. Similar to Praz et al. (2016a,b) we found mechanical efficiency being higher at steeper gradients.

Limitations

Even though we used standard skimo equipment, walking on the treadmill is somewhat different compared with walking on snow. However, a direct comparison of walking on snow and on the treadmill would be necessary to allow the transfer of results directly to the field. Additionally, the treadmill was limited in maximum gradient (24%) which can be judged as a medium gradient when skiing outdoors. Therefore, analysis of steeper slopes is warranted. Our protocol used the same speed for all gradients, which is an advantage when comparing biomechanical parameters, since the same walking speed was compared throughout the protocol, however, the strain on the participants was different across the three slope gradients. In particular, this difference in exercise intensity at different gradients could influence the locomotor patterns.

Conclusion

The purpose of this study was to compare the influence of riser heights and slope gradient on biomechanical variables during treadmill skimo and to learn more about the human-equipment interaction in skimo. Adjusting the riser height, dependent of the slope gradient, influences human–equipment interaction and changes movement patterns. Independently of the gradient, step frequency was increased by 5% when comparing the high riser height with the low riser height. In contrast to the low riser height, the high riser height increases the heel to toe drop during stance phase, which shortens step length, reduces swing time and reduces ROM of the knee and ankle joint. Additionally, the poles' impulse of forces and the pole angle are more beneficial when using the low riser height at the analyzed gradients. Mechanical efficiency suggests steeper gradients being more beneficial, while no difference concerning the applied heel riser heights was found. However, this does not exclude physiology being affected in any other way.

Since the high riser height indicates to influence the movement pattern negatively, especially at low gradients, we suggest applying the low riser height when ascending a gradient of 8%, while existing effects and interaction effects suggest changing toward the medium riser height when ascending the steeper tested gradients. This recommendation is supported by the comfort scale, which indicates the low riser height being most comfortable at 8% gradient and the medium riser height being most comfortable at 16% and 24% gradient. We did not find an indication for the highest riser height being the best choice at the analyzed gradients—not even the steepest tested gradient.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethical Committee of the University of Salzburg Universität Salzburg Kapitelgasse 4-6 5020 Salzburg, Austria. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ML, JS, TS, and A-MW contributed in an equal way to the conceptual and planning phase of the study. ML, JS, and A-MW were involved in data collection and annotated and improved this paper. ML and A-MW analyzed the presented data. ML wrote the first draft. All authors contributed to the article and approved the submitted version.

Conflict of interest

Author TS is employed by Red Bull Athlete Performance Center, Salzburg, Austria.

The remaining 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.

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Effects of physical stress in alpine skiing on psychological, physiological, and biomechanical parameters: An individual approach

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Alpine skiing is an attractive winter sport that often includes mental and physical demands. Since skiing is often done for several hours, fatigue processes occur that might lead to action errors associated with a higher risk of accidents and injuries. The aim of this study was to investigate the timing of changes in subjective, physiological, and biomechanical parameters during a physically demanding, standardized, non-competitive alpine skiing session. A group of 22 experienced male skiers carried out 10 runs, each lasting between 150 and 180 s, at a turn rate of 80 turns per minute with their best skiing technique. Immediately after the run, skiers reported ratings of fatigue, and other affective states. During skiing, breathing pattern and biomechanical data of the ski turns as radial force, turn duration, edge angle symmetry, and a composed motion quality score were recorded. Analyses of variances on skiers showing signs of fatigue (n =16) revealed that only the subjective data changed significantly over time: fatigue and worry increased, vitality and calm decreased. Subsequently, individual change points analyses were computed to localize abrupt distribution or statistical changes in time series data. For some skiers, abrupt changes at certain runs in physiological and/or biomechanical parameters were observed in addition to subjective data. The results show general effects in subjective data, and individual fatigue-related patterns concerning the onset of changes in subjective, physiological, and biomechanical parameters. Individuality of response to fatigue should be considered when studying indicators of fatigue data. Based on the general effects in subjective data, it is concluded that focusing on self-regulation and self-awareness may play a key role, as subjective variables have been shown generally sensitive to the physical stress in alpine skiing. In the future, customized algorithms that indicate the onset of fatigue could be developed to improve alpine skiers' self-awareness and self-regulation, potentially leading to fewer action errors.

KEYWORDS

individuality, holistic approach, physical load, fatigue processes, breathing pattern, experienced male skier, wearable sensors

Introduction

Alpine skiing is a highly attractive sport for many people, often practiced only a few days a year, but then for several hours. The combination of high motivation, comparatively little specific training, and an intensive acute physical and mental stress can lead to delayed or insufficient processing of fatigue. Action psychological approaches postulate that fatigue is a central predictor of action errors. The latter, in turn, are directly causally related to the occurrence of accidents and injuries (1, 2). Although some findings from occupational psychology indicate that work overload leads to increased susceptibility to errors and inaccuracy or to poorer perception of external stimuli (3, 4), there are few studies that have addressed changes in internal processes at the emotional, physiological, and coordinative level. Especially in sports activities with high coordinative and motor demands such as alpine skiing, it is critical to study processes that are associated with physical load against the background of the three systems approach (5). This approach, which originated in psychotherapy research, assumes that an emotional reaction is composed of subjective experience, physiological reactions, and overt behavior. Applying this approach to sport science research has the advantage that complex phenomena such as the effects of physical and mental stress associated with changes in fatigue state on self-regulatory processes can be studied holistically (6). The scientific findings of changes in psychological, physiological, and coordinative-motor processes could contribute to enhanced understanding of action errors in alpine skiing.

To date, few studies have been conducted with recreational alpine skiers analyzing short- and long-term changes in psychological, physiological, and biomechanical parameters. Most studies addressed exclusively physiological parameters such as heart rate and lactate (7, 8), or changes in muscle force (9) and muscle activity (9–11). To our knowledge, only one study has examined how psychological states change over three measurements in a skiing session of 3.5 h in elderly male and female recreational skiers ($M_{\text{age}} = 63 \pm 6$ years). Mood states were assessed 0.5, 1.5–2, and 3.5 h after skiing began. In contrast to our study, the participants were asked to ski in their usual skiing style, and they could take a break whenever they wanted. Minor significant increases of less than one on a 11-point Likert scale were observed for fatigue, sociability, and happiness, while no changes were found in the readiness for the activity, concentration, self-confidence, nervousness, anger, or worry (7). Therefore, for this study, we decided to standardize the physical task to elicit detectable sensations of fatigue with accompanying subjective, physiological, and motor-coordinative changes. A physiological approach was used by Seifert et al. (8) who investigated the relationship and predictors of common fatigue indices during recreational skiing in young females ($M_{\text{age}} = 22.7 \pm 4$ years) during 3 h of skiing. The length of the turns was administered by a standardized corridor, and they were instructed to maintain similar finishing times. Notably, it was found that heart rate does not appear to respond to fatigue (8), perhaps due to the many external influences during a day of skiing. Thus, we selected breathing as physiological indicator in this study, which was recently shown to be a sensitive indicator of signs of fatigue (12). Furthermore, there is empirical evidence that recreational skiing for 4 h is associated with a prolonged (at least 24 h) decrease in eccentric quadriceps and hamstring strength (9). This is in line with findings on electromyographic activity during a 3.5 h alpine skiing session in recreational female skiers indicating a significant decrease in the frequency content of the EMG signal with highest effects for the M. rectus femoris of the outside leg (10). In summary, there is little empirical evidence available regarding the time course of changes in subjective states, physiological, and motor-coordinative behavior throughout a typical skiing day.

It is reasonable to assume that with continued alpine skiing, changes in sensation of fatigue and related physiological parameters, as well as the quality of the skiing, will change. Determining the time course of these changes is necessary to gain further insight in the mechanisms involved in fatigue. In general, the intensity, type, and duration of a physical activity causes adaptions within the body (i.e., biochemical processes, breathing pattern) to maintain the performance, which in turn leads to changes on the central nervous system (13). In addition to these changes, the sensation of fatigue may change depending on physical exertion, training status (14), and psychological skills (15), which subsequently influences adjustments of the exercise strategy. Recently, a framework of fatigue proposed by Enoka and Duchateau distinguishes fatigability from fatigue. Fatigability was defined as an objective change in motor or physical performance, whereas fatigue describes a subjective sensation (16). In their work, fatigue is defined as "a disabling symptom in which physical and cognitive function is limited by interactions between performance fatigability and perceived fatigability", p. 2228. Accordingly, fatigue can only be determined by self-reports, which is confounded by an individual interpretation of relevant physiological and psychological changes. The sensation of fatigue depends on conscious and unconscious processes, and is unique depending on individual experiences (17). Hence, an individual approach is necessary to explore the complex relationship between fatigue and fatigability, which is considered both dependent and independent and implies many possibilities for fatigue processes (18). This framework is considered in the present study, with a central focus on the assessment of fatigue. The rate of fatigue scale (18) provides a single item questionnaire that can be easily used after each run to obtain reliable self-reporting on changes in fatigue over time. To detect broader, holistic signs of fatigue, affective well-being (subjective level), breathing patterns as indicators of perceived fatigability (physiological level), and biomechanical parameters of the skiing turn (overt behavior) as indicators of performance fatigability were measured. The measurement of these data in the context of a field study is possible thanks to recent technological developments that allow the recording of respiratory activity (19, 20) and biomechanical parameters relevant to alpine skiing (21–23) over several hours with sufficient accuracy and minimal interference to performance. It must be pointed out that, unlike heart rate, breathing pattern is highly sensitive to exercise-induced physiological processes (12, 24) including fatigue during alpine skiing (25). Finally, in addition to a general approach, it was prioritized an individual-focused statistical approach to carefully parse the relationship of fatigue, perceived fatigability, and performance fatigability between and within skiers.

The aim of this study was to investigate the timing of changes in subjective, physiological, and biomechanical parameters during a physically demanding alpine skiing session. To analyze general and individual changes relative to the phenomenon of fatigue two different statistical methods were used. We hypothesized that changes of sensations in fatigue would change individually with increasing duration of skiing, which would be associated with individual patterns of breathing and of the quality of the ski turn.

Methods

Participants

A sample of 22 experienced male alpine skiers participated in this study. Participants indicated that they have been regularly skiing for at least 10 years and started skiing during childhood ($M = 4.0$ years, $SD = 2.2$). Additionally, participants were asked to confirm beforehand whether they feel confident in adhering to an acoustically instructed turn frequency of 80 turns per minute. Table 1 shows age, anthropometric, and data on the fitness level of the skiers. The reasons for the selection of this sample were, first, to ensure that skiers can perform the task accurately, second, from an ethical perspective, it was important that the risk of injury was as low as possible, and third, to have a homogeneous sample because, for example, the subjective experience of women might differ from that of men. There were no falls during the entire test period. Participants confirmed that they were healthy and did not suffer from any neurological disorders or cardiovascular diseases. In the morning of the test day, the subjects and the investigators had to present a negative COVID-19 rapid antigen test. A FFP2 mask had to be worn on arrival and departure, when falling below a minimum distance of one meter and during the gondola ride. Furthermore, they were instructed to get enough sleep, drink sufficiently, and avoid hard training sessions the day before the skiing session, as well as to abstain from caffeine 2 h before starting the runs. The local ethics committee approved the study protocol. Each participant signed an informed consent.

TABLE 1 Sample characteristics ($n = 22$).

		M	*SD*	Range
Age (years)		26.9	5.4	20–45
Body weight (kg)		76.2	6.9	64.0–88.6
Body height (cm)		178.2	6.9	164.0–189.0
Age when started skiing (years)		3.98	2.2	2–10
Single-leg isometric F_{max} (N)	Right	1830.4	351.1	1362.7–2639.9
	Left	1751.7	311.5	1202.4–2300.8
Single-leg isometric F_{expl} (kN/s)	Right	45.8	12.9	31.9–74.4
	Left	41.6	12.7	10.2–74.4
VO_2peak (ml/min/kg)		50.6	6.6	34.6–62.6

Design and procedure

All data collection on the slope took place from 16.02.2021 to 06.03.2021 in Schladming, Austria. Snow conditions were mostly freshly groomed and grippy at the beginning of a testing day turning soft during the day. The weather conditions were sunny to partly cloudy without condensation. Temperature throughout the testing days was consistently between −2 and +4°C ($M = 2.00$, $SD = 2.17$) in the mornings, to −1 and +12°C ($M = 3.75$, $SD = 3.77$) at the end of the testing session. Since this was a north-facing slope, the effects on slope quality were very small, as indicated by biomechanical findings on ski turns (see Figure 4). Conditions changed little, if at all, across each person's 10 runs. Furthermore, because the tests took place during the Corona pandemic, very few people used the slope. One day before the alpine skiing experiment (t_0), participants were informed about organizational issues and the study procedure via video conference (WebEx, Webex by Cisco, Milpitas, CA, USA). Four weeks later, a broad physical fitness profile was collected including a single-leg isometric strength test and a measurement of peak oxygen uptake (VO_2peak). These measurements are used only to describe the fitness level of the skiers (see Table 1).

In this study, we chose a standardized protocol to ensure that we induced detectable sensations of fatigue and a comparable physical load. A preliminary study was conducted to determine the optimal number of runs that would produce a change in fatigue level of at least five points on a 11-point Likert scale and, at best, result in a state of totally fatigued. Accordingly, participants were instructed to perform 10 alpine skiing runs on a red slope [corresponding to Austrian Standards Institute (ASI); ÖNORM S 4611] at an Austrian ski resort (Planai, Schladming, altitude: 1,830–1,350 m, length: 2,200 m). All participants were provided with a Hexoskin (HX) smart shirt (Carré Technologies Inc., Montreal, Canada), which they wore throughout the experiment, and custom instrumented ski boots (Atomic Hawx Ultra 130, Atomic Austria GmbH, Altenmarkt, Austria). Participants completed the runs with their own skis. Prior to skiing, after five and ten runs, the participants completed a computerized cognitive task of around 5 min followed by a 5-min measurement of heart rate variability (HRV) at rest in a room of the cable car company at the middle station of the gondola at 1,350 m altitude. The data on cognitive performance and HRV are not focus of this article and therefore are not reported.

After a standardized warm-up guided by a certified skiing instructor, participants were asked to descend the slope while adhering to the prescribed turn frequency of 80 turns per minute. The turn frequency was administered with a smartphone application (Metronome Beats, Stonekick, London, UK) and in-ear headphones. Participants were to perform the maximum possible turn size while maintaining the set turn rhythm. Additionally, they were instructed to ski as much as possible using the carving turns as to demonstrate their "best possible" skiing technique in all runs. The first run served as a familiarization run to get used to the skiing slope and the pre-set turn frequency. During the runs, participants were followed by a skiing instructor who recorded their skiing performance using a handheld video camera. Immediately after the run, participants reported on their affective well-being. The experimental runs lasted between 150 and 180 s and the ride in the gondola lasted about 10 min. There was a break between the fifth and the sixth run of 30 min, during which participants were allowed to have a snack and to drink water (see Figure 1).

Materials

Subjective psychological data

Fatigue, the sensation that should be directly affected by the alpine skiing load, was assessed using the rate of fatigue scale (18). Against the background of the circumplex model of affect (26, 27), three further states of affective well-being were selected. The expressions in the dimensions of arousal (high/low) and valence (positive/negative) are considered by the states of vitality (high arousal and positive valence), fatigue (low arousal and negative valence), calm (low arousal and positive valence), and worry (high arousal and negative valence). Participants were asked to rate their state of vitality (28), fatigue (18), worry, and calm on an 11-point Likert scale ranging from 0 (not true at all) to 10 (totally true) beginning with "At this moment I feel…." The questions were asked by the accompanying ski instructor immediately after each run and the answers were recorded on a piece of paper.

Physiological data

Participants wore a HX shirt in all trials to gather respiration (dual thoracic and abdominal stretch sensors, 2 channel respiratory inductance plethysmography, 16-bit, 128 Hz) and heart rate (1 Ch ECG, 12-bit) data. Raw data were extracted via the HxServices application and the Hexoskin Online Dashboard. Breathing pattern was calculated with the algorithm of Harbour et al. (19) via MATLAB R2021a software (The MathWorks Inc., Natick, USA). Breathing rate (five-breath rolling average; breaths per minute) and depth (composite thoracic + abdominal amplitude; arbitrary units) was summarized on a per-run basis using average (mean), variability (coefficient of variation), and slope (between first 30 s and last 30 s average). Complete data sets are available for 12 subjects. In addition to the six participants who are excluded in the analyses on the subjective level, data from four skiers had to be excluded due to bad signal quality.

Biomechanical data

Two IMU's mounted to the upper posterior cuff of each ski boot measured 3D ski-boot acceleration and angular velocity signals during each skiing run (Movesense LSM6DSL, 2.5 × 3 × 0.83 mm, ±16 g and ±1,000 dps full scale resolution, ST Microelectronics, Amsterdam, Netherlands). The analog signals were sampled at 833 Hz, filtered, and transmitted to a custom smartphone application for storage and post processing at 54 Hz.

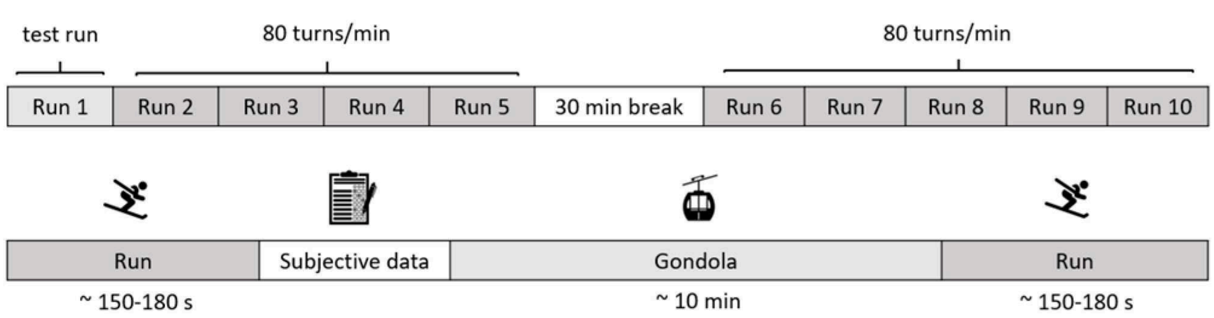

FIGURE 1
Design and procedure of the alpine skiing study. The first line provides an overall view of the procedure. The second line presents the procedure of within one run to the following run.

For further information regarding the wearable system, see Martínez et al. (22).

The turns were detected using the algorithm proposed previously by Martínez et al. (29, 30). The procedure utilized the mean angular velocity about the Z-axis (roll axis, pointing anteriorly) recorded from IMU's mounted on the upper posterior cuff of each ski boot. According to the inverted pendulum model frequently applied to alpine skiing, the time point of maximum angular velocity occurs when the pendulum is in the neutral position, or during the brief period between turns where the skier is not skiing, termed the turn switch. The algorithm uses a series of filters to first identify possible turn switch points and remove outliers, and second to "fine-tune" the identified turn switch points to find the most precise time point. Data were processed according to the extended activity recognition chain proposed by Brunauer et al. (31), where turns were segmented (29), and time normalized kinematic parameters including edge angle, radial force, speed, and edge angle symmetry were calculated for each turn (21). Based on these variables, turns were classified as carving, drifting, or snowplow (32), and finally assigned a quality score based on the motion quality algorithm (23). The last 30 turns of the runs two to ten were segmented (altitude ∼1,572–1,350 m) and an average over these turns was calculated. Four biomechanical indicators of motor-coordinative behavior were preselected so that the same number of variables were included in the change point detection analyses. The choice was based on theoretical considerations (standard deviation of turn duration reflecting the stability of turn timing) and effect sizes obtained by Kendall's W, selecting the parameters with the highest effect sizes (see Table 3). Accordingly, *turn duration, SD*, *edge angle symmetry, mean*, *radial force, mean*, and *motion quality score, mean* were determined (see Table 2). For completeness, descriptive and analytical statistics for the remaining variables are reported within the Supplementary materials (see Tables 3, 4). Due to data loss or synchronization problems with Bluetooth data, only complete data sets with no data-loss of 10 participants were considered eligible for analysis. To analyze comparable data sets, only data sets of participants who performed exactly 10 runs with no missing runs were included in the analysis.

Determination of participant's fitness level

Maximum voluntary and explosive single-leg isometric strength

The assessment of maximal voluntary and explosive strength was carried out on both legs separately in the leg-press position using a customized apparatus featuring a force plate. The knee angle was fixed at an angle of 100°. Signals were amplified by a DMCplus device (HBM, Darmstadt, Germany) and recorded with LabVIEW 6.1 software (National Instruments, Austin, USA). Maximum voluntary strength (F_{max}) was determined as the maximum value of force distribution and explosive strength (F_{expl}) as maximum force increase.

Peak oxygen uptake (VO_2peak)

A ramp incremental cycling protocol (LC7TT, Monark Exercise, Vansbro, Sweden) was applied to assess VO_2peak via a breath-by-breath spiroergometry system (ZAN600 Spiroergometrie, ZAN Austria e.U., Dietach, Austria). A 5-min warm-up interval at 70 W was followed by a load increase of 30 W per minute until exhaustion. Participants were instructed to maintain a cadence of about 80 rpm throughout the ramp test. VO_2peak was determined by calculating centered moving averages (15-breaths window) of breath-by-breath data during load increase. The "highest" moving average value was used as VO_2peak (33).

TABLE 2 Overview of the selected aiming variables.

Level	Variables	Description
Subjective level	Vitality	Scale from 0 to 10
	Fatigue	Scale from 0 to 10
	Worry	Scale from 0 to 10
	Calm	Scale from 0 to 10
Psychophysiological level	Breathing rate, mean	Respiratory frequency (breaths per minute)
	Breathing rate, cv	BR variability; quotient of standard deviation and mean BR (%)
	Amplitude, mean	Breathing depth; composite sum of thoracic and abdominal RIP amplitudes (arbitrary units)
	Breathing rate, slope	Slope difference between first 30 s mean BR and last 30 s within one run
Biomechanical level	Radial force, mean	Mean value of time normalized radial force (g)
	Turn duration, SD	Standard deviation of the turn duration (s)
	Edge angle symmetry, mean	Mean value of the differences in edge angle of both skis (°)
	Motion quality score, mean	Score consisting of edge angle, edge angle symmetry, and radial force, score from 0 to 10 (arbitrary units)

TABLE 3 Friedman's ANOVA for subjective, physiological, and biomechanical parameters.

	Friedman' s ANOVA		
	χ^2	*p*	*W*
Subjective parameters (*n* = 16)			
Vitality	62.2	<0.001†	0.49
Fatigue	94.5	<0.001†	0.74
Worry	83.6	<0.001†	0.65
Calm	33.6	<0.001†	0.26
Physiological parameters (*n* =12)			
Breathing rate, mean (bpm)	8.3	1.0†	0.09
Breathing rate, cv (%)	12.4	0.53†	0.13
Breathing rate, slope	5.2	1.0†	0.05
Breathing depth amplitude, mean (au)	12.9	0.46†	0.13
Biomechanical parameters (*n* = 10)			
Turn duration, SD (s)	16.6	0.14†	0.20
Edge angle symmetry, mean (°)	7.4	1.0†	0.09
Radial force, mean (g)	8.1	1.0†	0.10
Motion quality score, mean	14.0	0.32†	0.18

au, arbitrary units; cv, coefficient of variation; W, Kendall's W.
† Bonferroni corrected.

Statistical analyses

For the analyses of the subjective data, only participants were selected who completed 10 runs and demonstrated a change in fatigue of five points or more between the baseline (fatigue at rest at the beginning) and fatigue after the last run. This was to ensure that only participants who had a substantial change in fatigue of at least half the scale included in the analyses. Based on these criteria, four participants were excluded because they were totally fatigued after less than 10 runs, one participant showed too little change in fatigue (change of three points), and one participant scored calm and vitality with 10, and worry with zero at all measurements indicating that the scale was not understood. Thus, subjective data from 16 skiers were available for analyses. The sample size of physiological (n = 12) and biomechanical data (n = 10) is smaller due to movement artifacts and technical problems. For details see section Materials. Complete data sets including subjective, physiological, and biomechanical data are available for seven subjects.

The holistic approach taken in this study results in many dependent variables, which are summarized in Table 2. Two statistical approaches are used in this study. First, non-parametric univariate repeated measure comparisons (Friedman's ANOVA) were applied to get first insights about changes in subjective, physiological, and biomechanical parameters over time for the whole group. The familiarization run was not considered in the analyses. Shapiro-Wilk tests revealed significant deviation from normality for some runs for all parameters except breathing rate (mean), *breathing depth* (amplitude, mean), and the *motion quality score*. Computed effect sizes of Kendall's W were classified in small ($W \geq 0.1$ and < 0.3), medium ($W \geq 0.3$ and < 0.5), and large effects ($W > 0.5$) in accordance to Cohen (34). Skewness and kurtosis for all parameters are reported in the Supplementary materials. The significance level was set at $p = 0.05$ for each data level with Bonferroni correction for the number of variables per data level to avoid the accumulation of alpha errors. If significant changes were found, rank signed *post-hoc* tests were computed according to Dunn (35) and finally Bonferroni corrected. R Package *rstatix* was used for non-parametric univariate repeated measure comparisons and *post-hoc* tests (36).

In a second step, change points were computed to consider the individual changes within the subjective, physiological, and biomechanical data level separately and across all three data levels. The aim of change point detection algorithms is to localize abrupt distribution changes or changes of statistical properties in time series data (37, 38). To detect change points in the multivariate time series data, we chose a non-parametric estimation of the number of change points and their position of occurrence (38). In detail, the estimation is based on hierarchical clustering and a divisive algorithm. With this divisive method, no distribution assumptions had to be made in advance and neither prior knowledge of the underlying distribution family nor additional analysis is required to find distributional changes in multivariate time series data. The E-Divisive algorithm (38) can determine the number of change points and their location simultaneously. The definition of the number of change points is data driven and has not to be predefined. It uses a bisection procedure (39) and a divergence measure based on the concept of Euclidean distances and the work of Szekely and Rizzo (40).

For the analyses, change point detection via the R package *ecp* (41) and the *e.divisive* function was applied. We follow the explanation of the ecp package (41) to explain the general procedure of the algorithm. In the hierarchical divisive estimation, multiple change points are estimated by iteratively applying a single change point location procedure. The position of the change point is re-estimated at each iteration by dividing an existing segment. The flow of this method can thus be represented as a binary tree, where the root nodes represent the case where there are no change points and the entire time series is contained. The non-root nodes are a copy of the parent node or a new segment. The latter is created by adding a change point to its parent. A permutation test is used to perform the statistical significance of the estimated change points. This is necessary because the distribution of the test statistic results from the distributions of the observations, which in our case is not known (41).

Results

Non-parametric univariate repeated measure comparisons (Friedman's ANOVA)

Subjective parameters

Non-parametric repeated measure comparisons revealed significant differences between runs for all subjective parameters (see Table 3). *Vitality* gradually decreased significantly, while *fatigue* and *worry* increased significantly with continuation of alpine skiing. *Calm* changed significantly and showed a slight decrease from run two to run five, partially recovered at run six, slightly decreased again, and remained relatively stable from run seven to run ten (see Figure 2 and Supplementary Table 1).

For *fatigue*, significant Bonferroni corrected Dunn *post-hoc* findings were found between run two and runs eight, nine, and ten ($p_{\text{Run2vs.Run8}} = 0.03$; $p_{\text{Run2vs.Run9}} < 0.01$; $p_{\text{Run2vs.Run10}} < 0.001$), between run three and runs nine and ten ($p_{\text{Run3vs.Run9}} < 0.01$; $p_{\text{Run3vs.Run10}} < 0.001$), run four and run ten ($p_{\text{Run4vs.Run10}} < 0.01$) as well as run six and run ten ($p_{\text{Run6vs.Run10}} = 0.02$). *Post-hoc* tests for *vitality* showed a significant decrease between run two and run nine ($p_{\text{Run2vsRun9}} = 0.04$). *Worry* increased significantly between run two and runs nine and ten ($p_{\text{Run2vsRun9}} = 0.008$; $p_{\text{Run2vsRun10}} = 0.008$) as well as run three and runs nine and ten ($p_{\text{Run3vsRun9}} = 0.022$; $p_{\text{Run3vsRun10}} < 0.020$). No significant *post-hoc* differences between runs were determined for *calm*.

Physiological parameters

Non-parametric repeated measure comparisons showed no significant differences between runs in *breathing rate mean, breathing rate slope mean, breathing rate cv*, and *breathing depth amplitude* (see Table 3). For details on descriptive statistics see Figure 3 and Supplementary Table 2.

Biomechanical parameters

Turn duration SD, *edge angle symmetry*, *radial force*, and *motion quality score* revealed no significant change over the runs (see Table 3). For details see Figure 4 and Supplementary Table 2.

Change point detection

Figure 5 illustrates the detected change points in the time series for each data level separately. The x-axis shows the number of the run, and the y-axis represents the participant's code. If a change point has occurred, the rectangle is filled in blue for the respective run. The number of analyzed participants is indicated in the title bar of each sub-figure and ranges from 10 for biomechanical data to 16 for subjective data. Complete data sets were available from seven participants. In the subjective data, change points were obtained in nine of the sixteen participants. Six of the nine change points were noted immediately after the sixth run, which was preceded by a half-hour break. For the physiological data, change points were obtained in three out of twelve participants, while for the biomechanical data, two out of ten participants showed change points. Analyzing all three data level together, change points were found in three out of seven participants. About two-thirds of the observed change points occurred after the fifth and sixth run. The individual changes for each participant are reported within the Supplementary materials (see Figures 1–4). Individual patterns emerge in the combination of subjective, physiological, and biomechanical as well as when including all parameters that led to the detected change point.

The mean absolute changes of the z-transformed parameters after a change point are shown in Figure 6. For example, if a change point was observed after the sixth run, the absolute change compared to the fifth run is shown. Subsequently, the mean absolute change over all detected change points is calculated and shown in Figure 6 for each data level and for all variables. On average, the subjective data increased in *calm*, *vitality,* and *worry*, while *fatigue* remained relatively stable. Physiological data showed on average a remarkable increase in *breathing rate slope* and *breathing rate mean. Breathing depth amplitude mean* increased moderately and *breathing rate cv* was relatively stable. On the biomechanical level, the *motion quality score*, *turn duration SD,* and *edge angle symmetry mean* decreased on average, while the

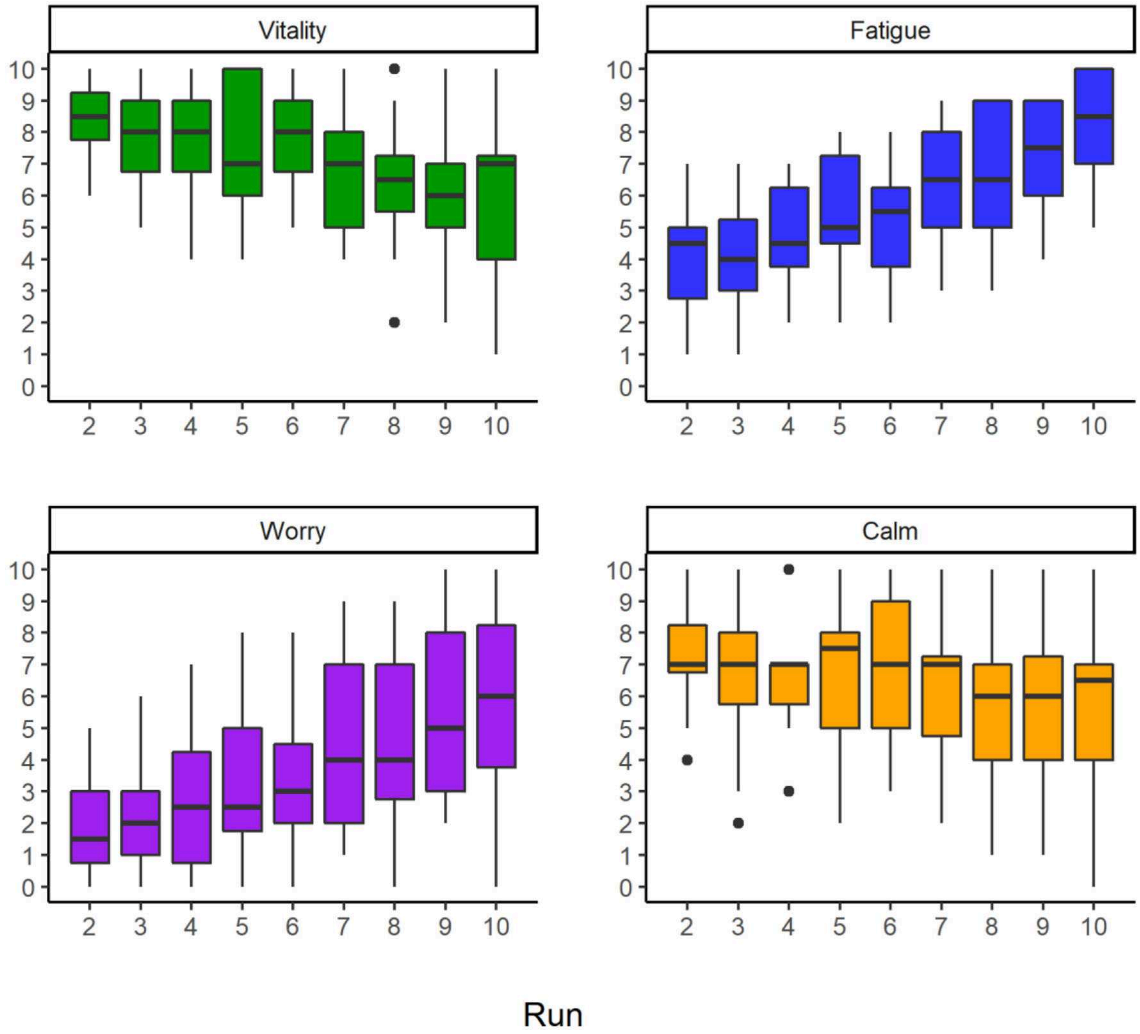

FIGURE 2
Boxplots including outliers (1.5 times of the interquartile range) indicated as black dots of subjective parameters (n = 16) per run.

radial force mean increased. Change point detection on all parameters showed on average an increase of more than one standard deviation in the *slope of the breathing rate,* an increase of about half a standard deviation in *fatigue* and a decrease of about half a standard deviation in *breathing depth amplitude mean*.

Discussion

This study examined changes in alpine skiing behavior against the background of the three systems approach (5) considering data on the subjective, physiological, and biomechanical levels. The aim of this holistic approach was to gain more knowledge on the processes that are associated with skiing-induced fatigue. Fatigue was considered as an individual sensation arising from the interpretation of perceived and performance-related factors (16). By combining a general statistical approach with an individual approach, general and individual trends were found.

Overall effects

Subjective level

In general, it was found that the study protocol resulted in a significant increase of *fatigue* with a large effect size (W = 0.74). In addition, the alpine skiing session led to a significant decrease in *vitality* (W = 0.49) and *calm* (W = 0.26), while *worry* increased significantly (W = 0.65). According to circumplex of affect (26), this can be interpreted

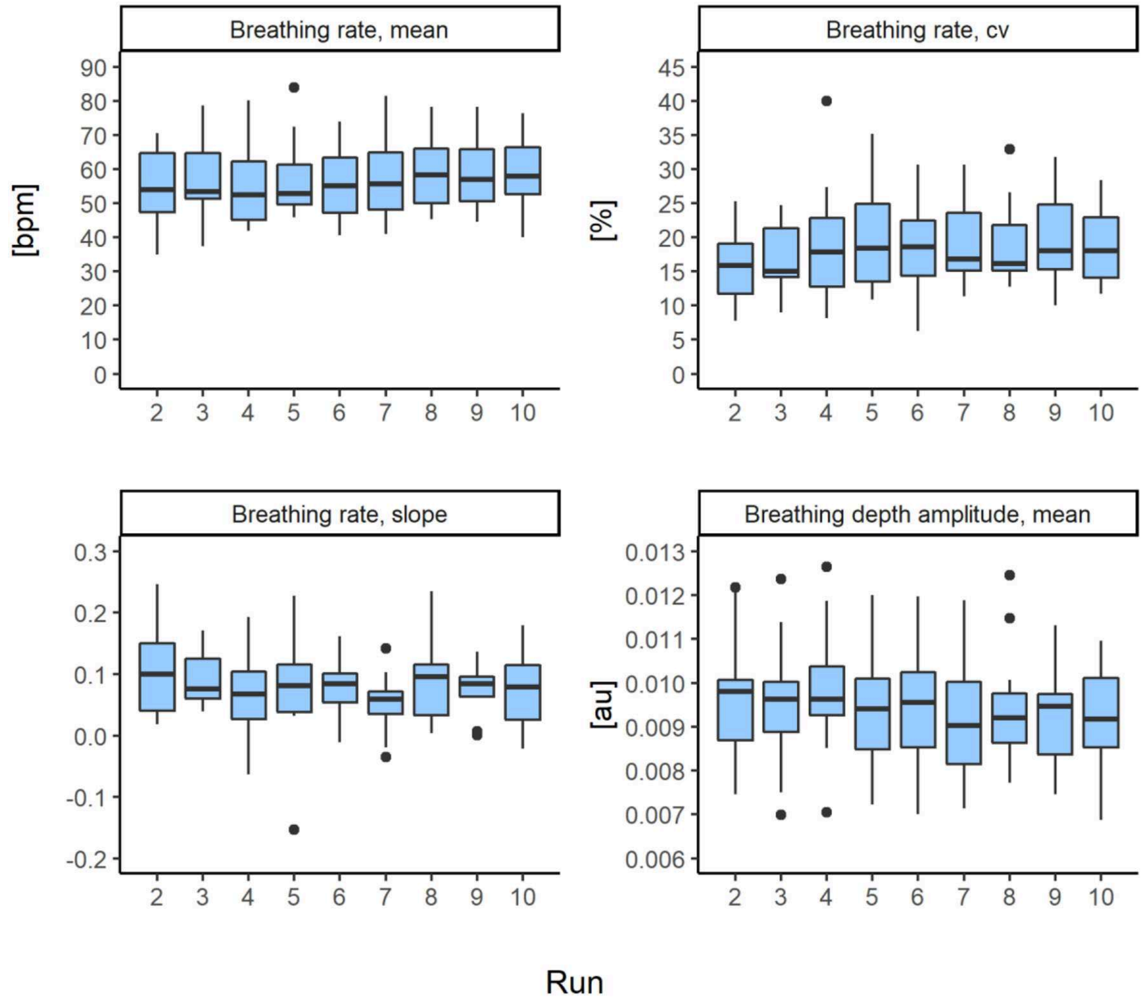

FIGURE 3
Boxplots including outliers (1.5 times of the interquartile range) indicated as black dots of physiological parameters ($n = 12$) per run.

that arousal decreases, and valence develops negatively by the alpine skiing session. The findings are not in line with a previous study, which reported an increase of positive valence despite an increase of fatigue in recreational skiers (7). The performance-oriented task of completing 80 turns per minute with the best skiing technique over nine runs may have led to doubts about not being able to fulfill the task, reflected in an observed sharp decline in *worry*. Overall, there is a small number of published studies of the effects on affective well-being during sports. Nevertheless, this study has contributed to this important topic by demonstrating that a standardized alpine skiing session leads to large changes in *fatigue,* which is accompanied by moderate to large changes in *vitality*, *calm,* and *worry*. The interrelation between these subdimensions was beyond the scope of this research but should be investigated in the future.

Physiological level

Physiological metrics exhibited non-significant, small effect sizes for pooled group data. However, about half of the skiers experienced an increased *breathing rate* across the skiing session, which was moderately correlated with fatigue ($r = 0.56$, $p = 0.02$). In a recent study on this data set, it was reported that some of the skiers did not increase *breathing* rate were performing some degree of Locomotor-respiratory coupling [breath and turn entrainment (25)]. Breathing coupled to fixed-tempo turning (as prescribed in this study) inherently leads to a stable *breathing rate*. It is unknown whether the coupling was done consciously or unconsciously; it could be driven by the rhythmic sound cues used in this study or biomechanical influences such as those present in running (42). Thus, future studies should investigate the development of breathing patterns during prolonged skiing when the turn frequency is self-selected.

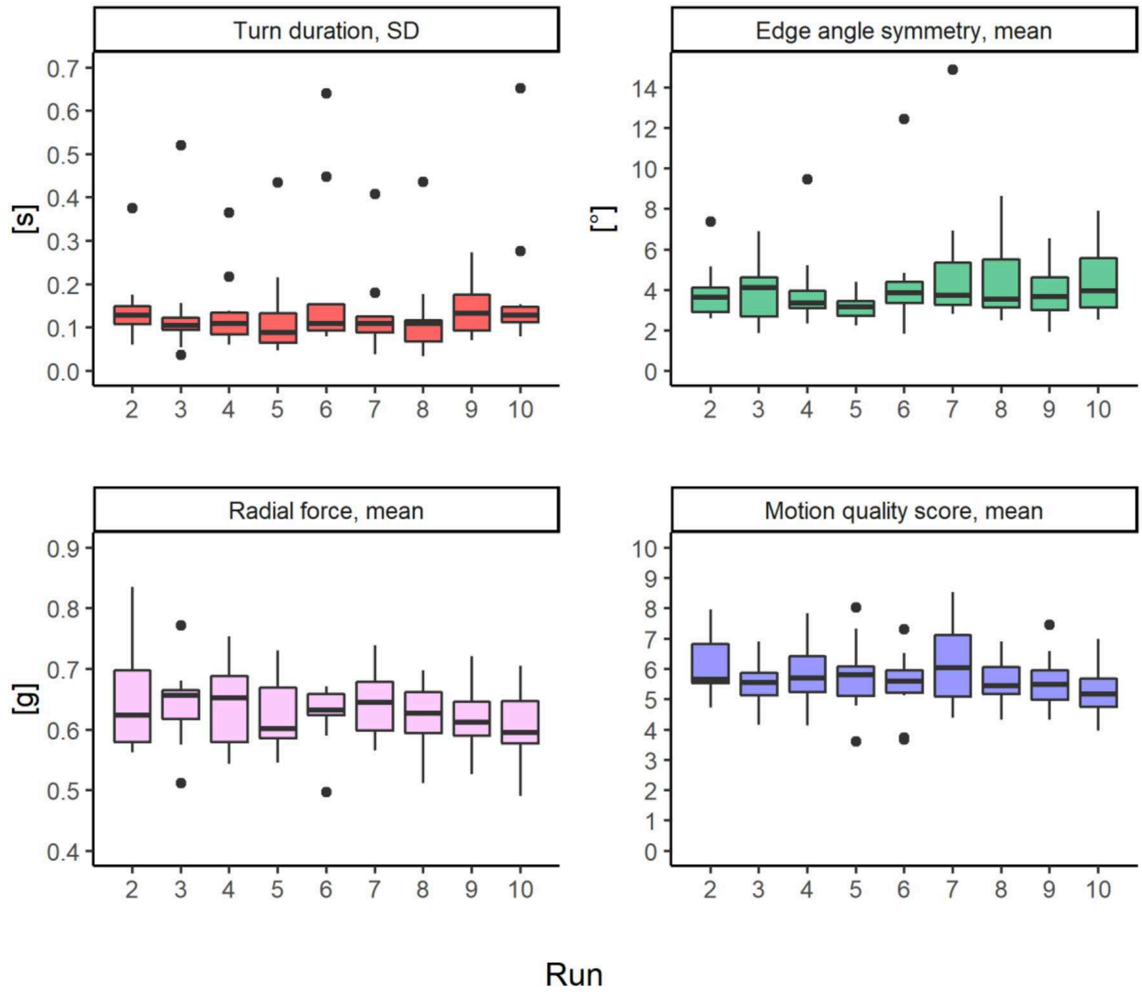

FIGURE 4
Boxplots including outliers (1.5 times of the interquartile range) indicated as black dots of biomechanical parameters ($n = 10$) per run.

Biomechanical level

Contrary to our expectation, no significant changes were found in biomechanical data indicating motor-coordinative behavior. Skiers maintained stable turn quality as estimated by the biomechanical parameters, can be maintained despite a high degree of fatigue. This contradicts previous studies analyzing EMG patterns and observations of the skiing technique (10, 11). Possibly, the experienced skiers have well-developed motor compensation strategies to accomplish the task of skiing 80 turns per minute with their best technique. There is empirical evidence that fatigue is associated with compensatory sensorimotor processes that set high cognitive load on the skier, possibly leading to a higher risk of action errors (43), an aspect that should be considered in future research. The fact that experienced skiers subjectively perceive a clear fatigue but do not show any deterioration in terms of skiing technique suggests that they are able to compensate for fatigue very well, presumably by making clever adjustments that allow them to still make a good turn. Whether this leads to an increased risk cannot be stated based on these data. Furthermore, we propose that investigations upon movement quality over long time periods should use more sophisticated methods than those used in this study to gain more knowledge on kinetic and kinematic changes.

Individual effects

Change points in the time series

Individual analyses were calculated to identify change points in the time data. While skiers had a diverse timing of change points in their subjective data, the sixth run was the most common significant change point. Notably, the relationship of the subjective variables to each other appeared to be unique between individuals (see

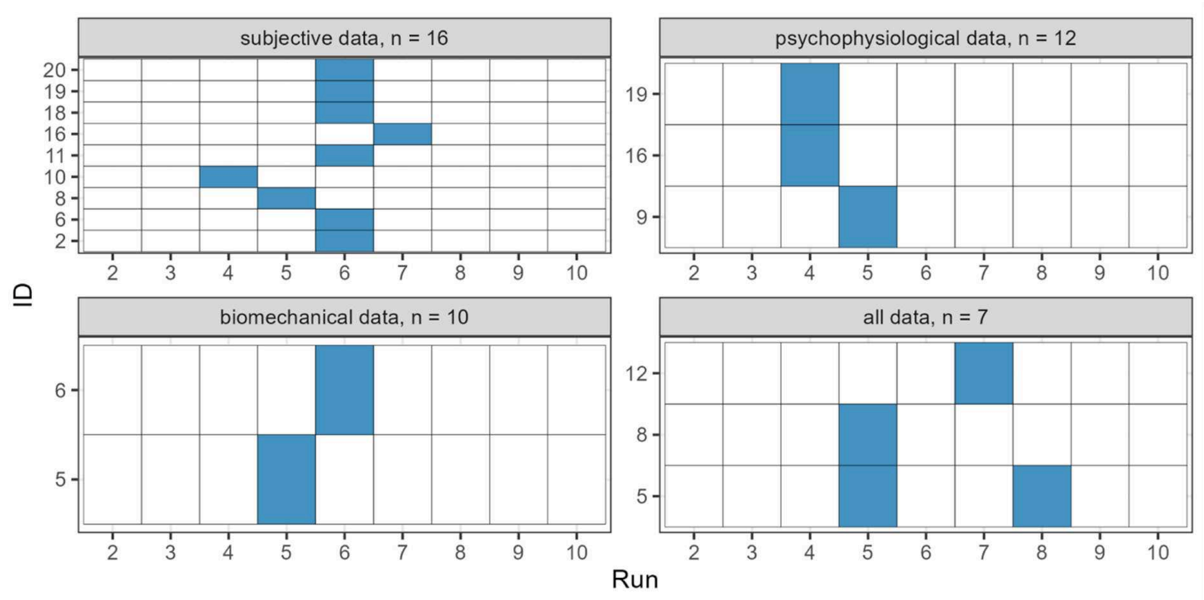

FIGURE 5
Detected change points in the time series; note that the number of participants, as indicated in the header, vary by data level; Subjective data consist of: fatigue, vitality, worry, and calm; psychophysiological data consist of: breathing rate, mean, breathing rate, cv, breathing rate, slope, and breathing depth amplitude, mean; biomechanical data consist of: turn duration, SD, edge angle symmetry, mean, radial force, mean, and motion quality score, mean.

Supplementary Figures 1–4). However, it should be mentioned that in seven out of sixteen participants no change point was detected.

Several unique individual patterns in physiological, biomechanical, and their inter-relationships were noted with respect to the timing of the change points. We interpret this to indicate that individuals cope with fatigue differently using different psychological abilities or skills that may lead to different patterns of physiological and biomechanical responses. Thus, one should consider excessive willingness and overconformity (44), coping strategies (45), and subconscious processes (17), as impactful factors upon the complex phenomenon of fatigue and its associated processes.

Effects at the change point

Finally, to gain insight into the subjective and objective changes at each of the detected change points, z-transformed scores were obtained for each variable. This provides valuable information about parameters that may be appropriate to indicate processes leading to fatigue in each individual. In this study, changes in the *motion quality*, the *breathing rate slope,* and *fatigue* were observed as indicators of the onset of fatigue. However, these parameters showed individual patterns and thus highlight the importance of an individualized approach.

Merged consideration on overall and individual effects

The approach of capturing change points helped to uncover trends that group-wide analyses would have missed. Without the individual approach, the main conclusion would be that only subjective data are sensitive to physical load in alpine skiing; nevertheless, subjective data responded to continued alpine skiing in nine out of sixteen participants. The perceived sensitivity to fatigue-related processes in more than half of the participants supports the notion that focusing on self-awareness and self-regulation may be a beneficial approach to manage prolonged physical stress. Furthermore, individual analyses showed that changes related to the physical task elicited different individual responses; for example, two participants experienced a change in the *motion quality score*, and three in the *breathing rate slope*. This indicates that individual responses must be viewed in a very detailed manner. Thus, we emphasize the importance of a holistic, intra-individual approach utilizing subjective and objective parameters when examining fatigue processes.

Limitations

The findings of this study must be considered with several limitations. First, the sample size of 22 participants was reduced

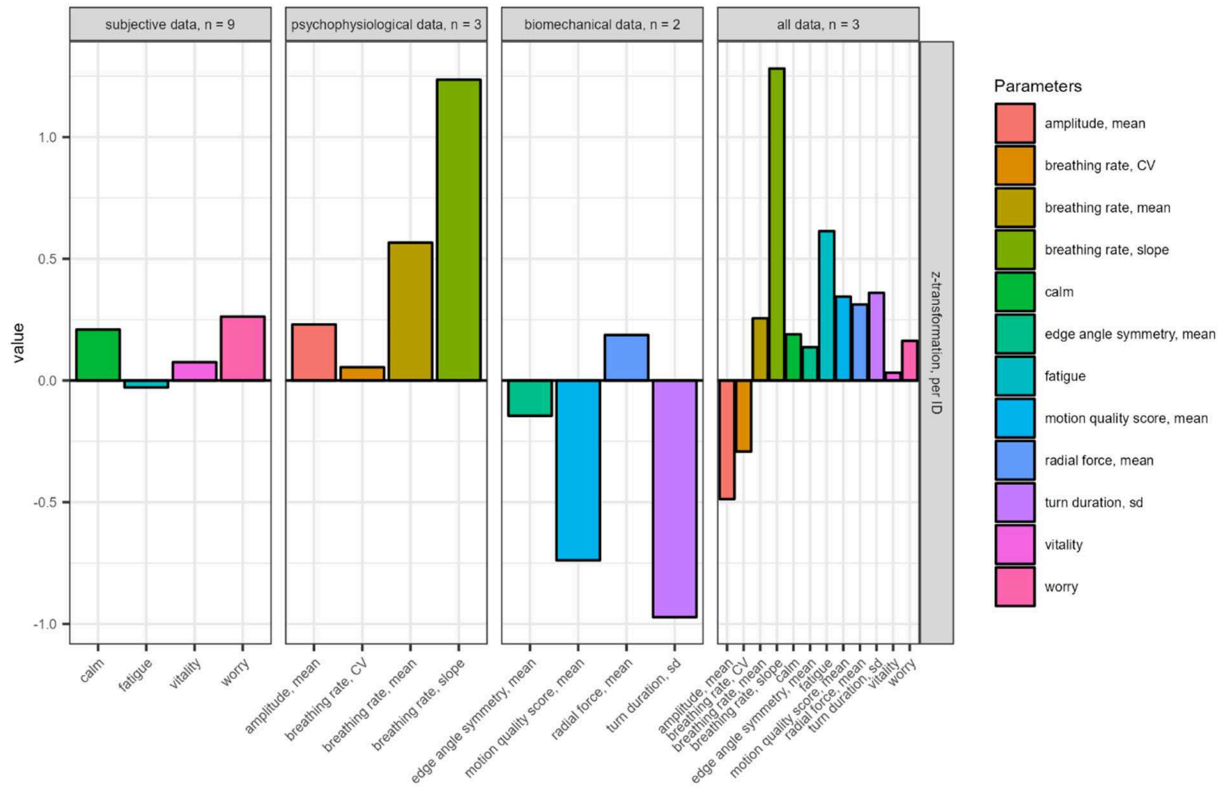

FIGURE 6
Mean absolute changes of the z-transformed parameters at the change point.

to 16 by the strict inclusion criteria regarding minimum number of runs completed and a definite change in fatigue. The number of participants from which valid physiological and biomechanical data were collected was only 12 and 10, respectively. Thus, the sample sizes are very small and differ between data levels. Therefore, it is essential to expand to these findings with more skiers and accurate data by using more sophisticated data processing, for example, with machine learning. Second, this study was conducted with experienced male alpine skiers and the findings are therefore limited to this specific group. Third, the alpine skiing session included to perform 80 turns per minute with the best skiing technique. This was introduced to standardize the physical load, with the goal of being totally fatigued after 10 runs; it is quite different from unconstrained recreational skiing. Fourth, the analyses are limited to specific parameters measurable with available wearable sensor technology.

Conclusion

This study showed that with the response to prolonged physical stress is highly individual. Research on fatigue in alpine skiing is still in its infancy, and little is known about inter- and intra-individual changes in the sensation of fatigue associated with perceived fatigability and performance fatigability. A more precise knowledge of the underlying processes triggered by the physical stress of alpine skiing could possibly contribute to a reduced risk of skiing accidents. However, future research needs to clarify how fatigue processes affect action errors and how this is causally related to recreational skiing accidents. Focusing on self-regulation and self-awareness may play a key role, as subjective variables are generally and in most of the individuals of this study sensitive to the physical and mental stress in alpine skiing. In the future, customized algorithms could be developed that provide feedback on ongoing fatigue processes based on sensitive parameters on the subjective, physiological, and biomechanical levels. This tool could help to train the self-awareness of fatigue in alpine skiing and thus improve the self-regulation of skiers, which in turn could have a positive effect on the risk of action errors.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary materials, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the Paris Lodron University Salzburg. The participants provided their written informed consent to participate in this study.

Author contributions

TF, GA, and SW: development of the research design. TF: writing—original draft preparation and visualization. TB: data collection, data processing, and statistical analyses. SK: change point detection. EH: processing of breathing parameters. CS: processing of biomechanical data. SW: statistical consulting. GA: responsibility for the entire project. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author CS was employed by company Red Bull Athlete Performance Center.

The remaining 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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.971137/full#supplementary-material

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Side-to-side differences in knee laxity and side hop test may predispose an anterior cruciate ligament reinjury in competitive adolescent alpine skiers

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An anterior cruciate ligament (ACL) injury is a common, severe injury in alpine skiing, and anterior cruciate ligament reconstruction (ACLR) is frequently performed in competitive alpine skiers younger than 20 years old. To reduce the reinjury rate, both intrinsic and extrinsic risk factors should be examined. The aim of this study was to investigate possible intrinsic risk factors for an ACL reinjury in competitive alpine skiers. A cohort of 384 alpine skiers (191 males/193 females) from the Swedish ski high schools were prospectively followed during their high school years. The students were clinically examined and physically tested prior to each ski season. In addition, the RAND 36-Item health survey 1.0 (SF-36, Copyright © 1994 Medical Outcome Trust, distributed by RAND Corporation) and injuries were prospectively registered. Thirty-one of the skiers (five males/26 females) had undergone an ACLR before entering the ski high school. This cohort was analyzed with respect to the occurrence of, and possible risk factors for an ACL reinjury (including ipsilateral and contralateral ACL injuries). Skiers who sustained an ACL reinjury were called the "ACL reinjury group," and those who did not sustain an ACL reinjury were called the "ACL injury group." Notably, 12 of the 31 students (39%), ten female and two male skiers, aged 16.5 (SD 0.5) years, sustained an ACL reinjury during the two first years at the ski high school. In addition, 10 of the 12 ACL reinjuries occurred within 10–23 months from the first injury [m 14.8 (SD4.7)] and two ACL reinjuries occurred at 29 and 47 months, respectively, from the first injury. It is noted that eight of the ACL reinjuries were to the ipsilateral knee and four to the contralateral knee. There were no differences between the groups with respect to muscle flexibility in the lower extremity, Beighton score, and one leg hop for distance or square hop test. Side-to-side differences were found with respect to knee joint laxity, >3 mm, measured with KT-1000 arthrometer ($p = 0.02$), and the side hop test ($p = 0.04$). RAND 36-Item health survey did not predict an ACL reinjury. In conclusion, a side-to-side difference in the side hop test and knee joint laxity (KT-1000) may predispose an ACL reinjury in competitive adolescent alpine skiers.

KEYWORDS

ACL injury, reinjury, alpine skiing, competition, adolescent, ski high school

Background

Competitive alpine skiing is an injury-risk sport, and the reports on injury incidence vary depending on how and when the incidence is reported. At the World Cup 2006/2007 and 2007/2008, the injury incidence was 36.7 injuries/100 alpine skiers (1), and at the Olympic games in Sochi, the injury incidence was 20.7 injuries/100 alpine skiers (2). An investigation by Fröhlich et al. (3) studying overuse and traumatic injuries in Swiss elite level skiers over one season showed an incidence of 95.5 injuries/100 alpine skiers. In high school competitive alpine skiers, the incidence of traumatic injuries was reported at 3.11 injuries/100 months attending a ski high school, and it was concluded that half of all the students were at risk for an injury during their 3–4 years of the study period (4). Around one-third of all alpine ski injuries are to the knee and the injuries on average generate more than 28 days of absence from the sport (1, 4). One of the most severe and common injuries to the knee is an anterior cruciate ligament (ACL) injury (5, 6). In a study by Pujol et al. (5) on 379 adult elite French alpine skiers over a period of 25 years, an incidence of 8.5 ACL injuries/100 competitive alpine skiers and season was shown. A total of 157 ACL injuries were registered, and half of the ACL-injured alpine skiers sustained an ACL reinjury to the ipsilateral or the contralateral knee (5). In another study, Stevenson et al. (7) described that 22% of alpine skiers underwent a second ACL reconstruction (ACLR). The general opinion is that an ACLR is necessary to be able to continue with alpine skiing and is frequently performed in young competitive alpine skiers.

To reduce the ACL reinjury rate, both intrinsic and extrinsic risk factors should be examined. Side-to-side differences, decreased core stability, and parents' history of an ACL injury are intrinsic factors mentioned as risk factors for the first ACL injury in alpine skiing (8–10). Risk factors for an ACL reinjury in football seem to be injury events close to previous ACLR (11) or time to return after an ACLR (12) as well as whether it was a contact or non-contact ACL injury the first time. Non-contact injuries and isolated ACL injuries were injury risks for an ACL reinjury in professional footballers (13). Another risk for an ACL reinjury seems to be a young age. Paterno et al. (14) showed that 25% of the athletes returning to pivoting sports, and under the age of 25 years, sustained an ACL reinjury. In a 5-year follow-up from the Swedish National Knee Ligament Register (SNKLR), it was shown that athletes under the age of 20 years at the first ACLR had an almost three-fold risk for a contralateral ACL injury to occur (15). A review on ACL injuries showed that close to one of four athletes (23%) under the age of 25 years, returning to high-level sports with an ACLR, sustained an ACL reinjury (16).

To recover and return to sports after an ACL injury is difficult, and the perfect algorithm is still not known. Biological healing and functional performance are keys to success (17). Another key is mental health and psychological readiness to return to play (18, 19).

To the best of our knowledge, studies on risk factors for sustaining an ACL reinjury in young alpine skiers are still lacking. Therefore, the overall aim of this study was to investigate possible intrinsic risk factors for an ACL reinjury in young competitive alpine skiers during their ski high school years. The second aim was to describe this sub-cohort of students from a health perspective using the RAND 36-Item health survey 1.0 (SF-36, Copyright © 1994 Medical Outcome Trust).

Methods

A cohort of 384 alpine ski students (191 males and 193 females), from ten different Swedish ski high schools, were prospectively followed from September 2006 to May 2009 with respect to performance and injury incidence. A ski student attends high school for 3 or 4 years and is exposed to approximately 200 days of skiing per year (4). The students were included in their first year at the ski high school, and this study was approved by the Swedish Ethical Review Authority, Dnr 2006/833-31/1. Oral and written consent was collected from the ski students.

Of the included 384 ski students, 31 students (five males and 26 females) had undergone an ACLR before entering the ski high school (Table 1). This subgroup of skiers was followed during their studies at the ski high school and in this study occurrence of an ACL reinjury, and possible risk factors for sustaining an ACL reinjury during the ski high school years were analyzed. In this study, the group with skiers sustaining an ACL reinjury is called the "ACL reinjury group" and includes an injury to the ipsilateral or contralateral ACL. The group of skiers that did not sustain an ACL reinjury during their high school years is called the "ACL injury group."

TABLE 1 Demographic data of the 31 ski high school students who entered the study with a previous anterior cruciate ligament reconstruction (ACLR).

ACLR at school start		Male ski students $n = 5$	Female ski students $n = 26$
Age	m (SD)	16 (0)	16.3 (0.5)
Height (cm)	m (SD)	175.2 (4.9)	166.3 (5.2)
Weight (kg)	m (SD)	72.4 (9.9)	63.3 (7.1)
Body mass index (BMI)	m (SD)	23.5 (2.6)	22.9 (2.0)
ACL injury left knee	*n*	5	14
ACL injury right knee	*n*	0	11
ACL injury bilateral	*n*	0	1

m, mean value; SD, standard deviation; n, number.

All ski students were clinically examined and physically tested prior to each ski season according to a specific protocol previously described by Westin et al. (8). The protocol included muscle flexibility of hamstrings, rectus femoris, iliopsoas, gastrocnemius, soleus (8), general joint laxity measured with Beighton score (20), knee joint laxity measured with KT-1000 arthrometer (21), and functional performance tests such as the one leg hop for distance, side hop test, and square hop test (22–24). General joint laxity, the Beighton score, was classified as yes ($\geq$ 5 of nine positive tests) and no ($\leq$ 4 positive tests). The skiers also answered the RAND 36-Item health survey 1.0 (25) (SF-36, Copyright © 1994 Medical Outcome Trust), and ACL injuries were prospectively registered.

The items in the RAND 36-Item health survey consist of 36 questions regarding physical functioning (10 questions), bodily pain (two questions), role limitations due to physical health problems (four questions), role limitations due to emotional problems (three questions), emotional wellbeing (five questions), social functioning (two questions), energy/fatigue (four questions), general health perceptions (five questions), and at last a single question regarding the perceived change in health since last year. The questions were presented in a mixed order and adapted from a more extensive instrument used in the Medical Outcomes Study (MOS) (26). The scoring system is a two-step process where all the questions in the survey are evaluated on a scale from 0 to 100, and thereafter, the questions that answer each of the eight plus one domain are summarized and averaged. When summarized, 0 represents poor health and 100 represents good health. For more information, visit RAND Corporation (https://www.rand.org/health-care/surveys_tools/mos/36-item-short-form/scoring.html).

Statistics

Data were presented descriptively with mean values and standard deviation (m(SD)) or with median and interquartile (md(IQ)) or total range (md(range)). Chi-squared test was used analyzing general joint laxity, and the Mann-Whitney *U*-test was used comparing side-to-side differences in the preseason tests between the "ACL reinjury group" and the "ACL injury group" (27). The RAND 36-Item health survey 1.0 (SF-36, Copyright © 1994 Medical Outcome Trust) was recorded and analyzed according to recommendations by RAND Corporation, and the eight domains were presented with md (total range) for both groups. The preseason measurements prior to the ACL reinjury season were used for the "ACL reinjury group," and the preseason measurements from year 2 in the "ACL-injury group" served as control values, though in six cases, the preseason tests from year 1 were used due to missing values in year 2. The *p*-value was set at $\leq$0.05.

Results

Out of 31, 12 (39%) students, ten female and two male skiers, m 16.5 (SD 0.5) years old, sustained an ACL reinjury. The injuries occurred on average 18.7 months (SD 10.8, range 10–47) from the first ACL injury. Notably, 10 of the 12 ACL reinjuries occurred within 10–23 months from the first injury [m 14.8 (SD 4.7)], and two of the ACL reinjuries occurred 29 and 47 months, respectively, after the first ACL injury. Six ACL reinjuries occurred during the first year at the ski high school (two males/four females) and six ACL reinjuries occurred during the second year (six females). Eight of the ACL reinjuries were to the ipsilateral knee and four reinjuries to the contralateral knee. Ten of the ACL reinjuries were to the left knee and two reinjuries to the right knee. One male skier reinjured his left ACL, and the other male skier injured his right knee, which was the contralateral ACL. Six female skiers reinjured their left ACL, three female skiers injured their contralateral knee of whom two injured their left ACL, and one injured her right ACL (Table 2).

There were no differences between the "ACL reinjury group" and the "ACL injury group" with respect to muscle flexibility in hamstrings, rectus femoris, iliopsoas, gastrocnemius, or soleus measured according to the protocol presented by Westin et al. (8), or with respect to general laxity measured with Beighton score, or in the functional performance tests, one leg hops for distance or square hop test. Significant differences were found with respect to knee joint laxity measured with KT-1000 max manual where >3 mm is considered a side-to-side difference and the side-to-side differences in the side hop test. Skiers in the "ACL reinjury group" had a side-to-side difference in knee laxity

TABLE 2 Alpine ski high school students who sustained an ACL reinjury.

		Male *1st ACL-injury*	**Male *2nd ACL-injury***		**Female *1st ACL-injury***	**Female *2nd ACL-injury***	
Left knee	n	2	1		7	8	
Right knee	n		1		3	2	
Months between 1st and 2nd injury	m (SD) range			12 (1.4)11–13			20 (11.4) 10–47

Injured knee at 1st and 2nd injury and the average number of months between the two injuries ($n = 12$). n, number; m, mean value; SD, standard deviation; range (min-max).

TABLE 3 Skiers who answered the RAND 36-Item health survey at the start of the preseason tests used in this study.

RAND 36-Item health survey	Skiers who answered the health survey $n = 29$	
	"ACL reinjury" $n = 11$	"ACL injury" $n = 18$
Physical functioning	100 (85–100)	97.5 (77.8–100)
Role limitations due to physical health	100 (25–100)	100 (0–100)
Role limitations due to emotional problems	100 (66.7–100)	100 (66.7–100)
Energy / fatigue	70 (50–100)	75 (40–100)
Emotional wellbeing	80 (64–100)	84 (52–100)
Social functioning	100 (75–100)	100 (37.5–100)
Pain	77.5 (47.5–100)	77.5 (35–100)
General health	75 (46–100)	86.8 (45–100)
Health change from the year before*	75 (0–100)*	50 (50–100)*

*One question where 50 = same health as last year, and >50 = better health than last year. Each item is scored from 0 to 100 where 0 = poor health and 100= good health. Data are presented with median and total range values.

of md 4 mm (IQ 3–5) compared with skiers in the "ACL injury group" with a side-to-side difference of md 1 mm (IQ 0–3) ($p = 0.02$). In the side hop test, the side-to-side difference was md three hops (IQ 3–4) in the "ACL reinjury group" compared with md two hops (IQ 1–3) in the "ACL injury group" ($p = 0.04$). The RAND 36-Item health survey did not predict an ACL reinjury (Table 3).

Discussion

Nearly, two-fifths (39%) of the ski students entering a ski high school with an ACLR sustained an ACL reinjury within the two first years at the ski high school. The average age for an ACL reinjury was 16.5 years, and the average time from the first ACL injury was 18.7 months. However, 10 of the 12 ACL reinjuries occurred 10–23 months from the first ACL injury, which, on average, was 14.8 months from the first injury. The result is in line with previous research showing that an ACLR before the age of 20 combined with return to high level activity, predisposes an ACL reinjury (11, 16, 28, 29).

Skiing is an equilateral sport, which means that the ski turns have to be equally good to the left and to the right side, and consequently it is important to be equally good on both sides in functional performance tests. Previous research has shown a side-to-side difference to be a risk factor for an ACL injury in alpine skiing (8). This was also shown in this study where the ACL reinjury group had a larger side-to-side difference in the side hop test and in knee laxity measured with a KT-1000 arthrometer compared with those skiers who did not sustain an ACL reinjury. The side hop test may be considered a skiing-like hop test since the hop movement is performed from side to side. In this study, the difference between the groups was small, though significant, but maybe just the difference between mastering a ski turn equally good in both directions or not. Previous research has used limb symmetry index (LSI) to evaluate side-to-side differences between injured and uninjured legs in alpine skiing (30). However, in this study, where the students entered with an ACLR, this was not optional. In an injury profile study in ski high school students, the left leg was more injury prone than the right leg (4). One might speculate that, since most humans are right-sided, the left leg might be more vulnerable due to the equilateral demands of alpine skiing. Ten out of 12 ACL reinjuries in this study were in the left knee, and the reinjuries occurred more frequently in the ipsilateral knee compared with the contralateral knee, consequently more frequently to the left knee compared with the right knee. It could be of importance to understand whether a skier is right- or left-dominant in order to put special focus on the less dominant side with the aim to become equilateral.

Another highly important finding was based on the RAND 36-Item health survey all students entering the ski high school with an ACLR reported fairly low levels in the items energy/fatigue, pain, and general health compared with the other items and compared with normative data (31). Do the skiers return to skiing before fully recovered from their first injury? Nagelli and Hewett (17) suggested that return to unrestricted sports activity should be delayed until 2 years after an ACLR. This was based on biological and functional recovery. For example, the ligamentization process of the ACL autograft in humans may take up to 1 year for the patella-tendon autograft and 2 years for the hamstrings autograft (17). In addition, the neuromuscular system has to recover as well as bone and muscular strength, and sports-specific skills must be regained.

To recover and return to sports after an ACL injury is difficult. Considering the short time between the ACL injuries, one might suspect that the students were fighting with recovery from the first injury. In a study on gymnasts' experiences and perception of an ACL injury, the gymnasts described that early contact with a sports psychiatrist or likewise is important (30). They also described that one can become and feel stronger than ever, but if one does not prepare the body and mind for the specific gymnastics skills, one cannot succeed in the aim of returning to the previous level of gymnastics. Psychological readiness is a crucial part of returning to sports and may be the difference between whether the athlete returns to high-level sports or not (18, 19, 32, 33).

This study investigated students at ski high schools from year 1 to year 4. To attend a ski high school means leaving family behind and moving to a new place at a young age. In addition, these young students entered the school with a previous ACL injury and according to the health survey, with fairly low levels of energy, pain, and estimated general health. Maybe these alone are risk factors for an ACL reinjury, even if it was not shown in this study. In a study on young elite athletes, attending sports high school with a mean age of 17.1 years, it was found that sleeping 8 h or more and reaching recommended levels of nutrition intake reduces the odds to sustain an injury by more than 60% (34).

To prevent severe knee injuries in young competitive alpine skiers probably needs an algorithm including prevention based on risk factors and physical as well as psychological recovery in between training and competition. To date, only two prevention programs have been carried out on adolescent alpine skiers. In a study by Schoeb et al. (35), an off-snow injury prevention program for Swiss aged under 16 years (U16) competitive skiers performed once a week, reduced the 2-weekly prevalence of knee trauma, knee overuse, and lower back overuse complaints. Another study by Westin et al. (36) using a neuromuscular prevention program on- and off-snow, showed a reduction of first episode ACL injury in competitive alpine skiers between 16 and 20 years of age. Both these programs were carried out during the whole skiing season. In addition, psychological preparation must be included. This may be provided by the ski trainer, mental coach, medical team, family, or friends. For example, a young skier, attending a ski high school, does, in most cases, leave the secure environment at home for security provided by the school, friends, and the skiing community. Just to have someone to talk to, preferably someone with knowledge of alpine skiing, not involved in the regular ski training, could be one way of providing psychological preparation, security, and readiness to the skiers (32).

The fact that the students were followed prospectively from day 1 at the ski high school until they left the school 3–4 years later may be seen as a strength of this study. The students entered the school with a previous ACL injury, which made it possible to study ACL reinjuries. One limitation is that information about the first ACL injury is scarce, and the health status before the first ACL injury is unknown. Another limitation is the small sample size.

Conclusion

Out of 31, 12 ski high school students (39%) entering the school with an ACLR sustained an ACL reinjury during the first 2 years at a ski high school and on average 18.7 months from the first ACL injury. Side-to-side differences were found in the side hop test and knee joint laxity, measured with the KT-1000 arthrometer, and may predispose an ACL reinjury in competitive adolescent alpine skiers. RAND 36-Item health survey did not predict an ACL reinjury.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by Swedish Ethical Review Authority, Dnr 2006/833-31/1. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MW and MH have given substantial contribution to the conception, design of the study, and drafted the manuscript. Acquisition of data by MW. Analysis and interpretation by MW, LM, and MH. All authors critically revised, read, and approved the final version of the manuscript.

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Conflict of interest

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.

Publisher's note

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Contribution and effectiveness of ski and pole forces in selected roller skiing techniques on treadmill at moderate inclines

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Background: Most of the studies about the effects of incline on cross-country skiing are related to the metabolic efficiency. The effective skiing biomechanics has also been indicated to be among the key factors that may promote good performance. The aims of this study were to provide biomechanical characteristics and investigate the relative contribution and effectiveness of ski and pole forces in overcoming the total external resistance with double poling (DP) and Gear 3 (G3) techniques at varying moderate uphill inclines.

Methods: 10 male cross-country skiers participated in this study. Custom-made force measurement bindings, pole force sensors, and an 8-camera Vicon system were used to collect force data and ski and pole kinematics at 3°, 4° and 5° with 10 km/h skiing speed.

Results: The cycle length (CL) decreased by 10% and 7% with DP and G3 technique from 3° to 5° ($p < 0.001$, $p < 0.001$). The cycle rate (CR) increased by 13% and 9% from 3° to 5° with DP and G3 technique respectively. From 3° to 5°, the peak pole force increased by 25% ($p < 0.001$) and 32% ($p < 0.001$) with DP and G3 technique. With DP technique, the average cycle propulsive force (ACPF) increased by 46% ($p <$ 0.001) from 3° to 5°and with G3 technique, the enhancement for ACPF was 50% ($p < 0.001$). In G3 technique, around 85% was contributed by poles in each incline.

Conclusion: The higher power output in overcoming the total resistance was required to ski at a greater incline. With DP technique, the upper body demands, and technical effectiveness were increasing with incline. With G3 technique, the role of external pole work for propulsion is crucial over different terrains while role of legs may stay more in supporting the body against gravity and repositioning body segments.

KEYWORDS
double poling technique, gear 3 technique, speed maintain, crosscountry skiing, effectiveness

1. Introduction

Cross-country (XC) skiing is a sport in which competition and training are normally performed on varying track topography. The classical and skating style (also known as freestyle) are the two basic skiing techniques. Techniques such as double polling, diagonal stride, and kick double pole, are sub-techniques of classical skiing technique (1). In skating technique, there are six different sub-techniques, so called gears (Gear 2-Gear 7) (2, 3). In both classical and skate skiing, skiers change the sub-techniques spontaneously to maintain high speed and adapt to the change of the terrain (4–6). Several researchers have studied the effect of incline and speed on metabolic efficiency (7–9), technique shift (5, 10), as well as kinematics and kinetics change (11–16). The effects of incline on metabolic efficiency have been studied a lot (7–9), as it is a key factor for endurance sports (17). The effective skiing biomechanics has also been indicated to be among the key factors that may promote good performance (18). Therefore, having more knowledge about the effects of incline on skiing biomechanics may be beneficial for skiers and coaches with skiing technique improvements for maintaining the skiing speed at varying uphill inclines.

Several studies have investigated the effects of incline on cycle and force characteristics of different skiing techniques. The cycle rate (CR) has been proved to be higher at steeper inclines (4, 19). In both DP and Gear 2 (G2) technique, the peak pole force (PPF), average pole force and average cycle pole force were all greater at the higher incline situations (19). The primary mechanical determinant of skier's performance is the propulsive force (1), which has been defined as the forward directed component of the 3D resultant reaction force from skis and poles acting on skiers (1, 16, 20–22). The total external resistance should be overcome by the total propulsive force in XC skiing. However, less works (16, 22) have examined the effects of incline on the forces and propulsive forces generated from skis.

As one of the main techniques in classic XC skiing, the usage and the importance of DP technique have been increased during the past years due to increased upper body power, more systematic strength training and higher skiing speeds (20, 23). The Gear 3 (G3) technique has also become the most commonly used technique in the freestyle XC skiing competition (24). DP and G3 technique are normally used in level terrain up to moderate uphill inclines. The DP technique, which involves both arms acting in unison and leg involvement, has often been considered as an upper-body movement (25–27) as the propulsive forces are exerted only through the poles even though it is clear that also legs contribute to the performance (28, 29). The G3 contains symmetrical pole thrust on every leg stroke (1). The propulsive force in G3 are generated from both skis and poles (30, 31). Although most of the total propulsive force has been proved to be attributed to the forces from poles in skate skiing techniques (32, 33), how the ski and pole forces are performed to maintain the speed with varying uphill inclines need further investigation.

Therefore, the current study was conducted to (1) provide biomechanical characteristics and (2) investigate the relative contribution and effectiveness of ski and pole forces in overcoming the total external resistance of both DP and G3 techniques at varying moderate uphill inclines. We hypothesized that with DP technique, we could measure some propulsive forces from skis, but it would be quite small, and pole forces would be more effective at steeper inclines than at relative lower inclines. We also hypothesized that pole forces contribute more and would be more effective than the ski forces with G3 technique (32, 33) in overcoming the total resistance at any incline, but the relative contribution of ski forces to overcome the total resistance would increase at steeper grade.

2. Materials and methods

2.1. Participants

10 male participants (age: 29.4 ± 7.9 years; height:181.4 ± 5.7 cm; weight:77.9 ± 8.9 kg) who were familiar with treadmill roller-skiing volunteered to participate in this study. The participants' group included experienced skiers, such as high-level junior athletes, recently retired athletes from the national team, local skiing club members and national team coaches, both latter ones are with high roller skiing skill and fitness levels. All protocol used in this study were approved by the Ethics Committee of the University of Jyväskylä. All participants were provided written informed consent before the measurement and were free to withdraw from the experiments.

2.2. Protocol

Passive reflective markers were attached onto skiing equipment before the measurement. First, participants completed a 10–15 min warm-up roller skiing on the treadmill. After the warm-up activity, the DP technique was performed at 3°, 4° and 5° at a speed of 10 km/h. This speed is commonly used in aerobic capacity tests where the speed is kept constant. There was a 1-min rest between each incline. When the DP technique was done, pole length was adjusted to a comfortable length for G3 technique (1). The comfortable pole length for DP technique were 85.9% ± 2.5%, and for G3 were 90.0% ± 1.3% of skiers' body height in this study. The participants were given a 5-min rest period while adjusting the pole length. The G3 technique was then performed on the treadmill. The protocol for changing the incline was the same as during the DP test.

2.3. Data collection

An 8-video-camera motion capture system and NEXUS 2.8.1 software (Vicon, Oxford, United Kingdom) were used to collect and record the three-dimensional (3D) trajectories of reflective markers at a sampling rate of 150 Hz. The global coordinate system (GCS) was defined by using the right-hand rule when the incline of the treadmill was 0° and was calibrated according to Vicon's specifications. The Y-axis of GCS was defined as the longitudinal axis of the treadmill. The Z-axis of GCS was perpendicular to the ground pointing upward. 15 reflective markers were used in this study. 6 markers were attached onto the roller skis (3 markers each, **Figure 1**) and 6 markers were attached onto the poles (3 markers each, **Figure 1**). Another 3 markers were attached onto the treadmill. Two markers were attached to the front and rear right corners of the treadmill. Another one was attached to the rear left corner of the treadmill. All markers in this study were used to provide the position of roller skis, poles, and the treadmill in the GCS.

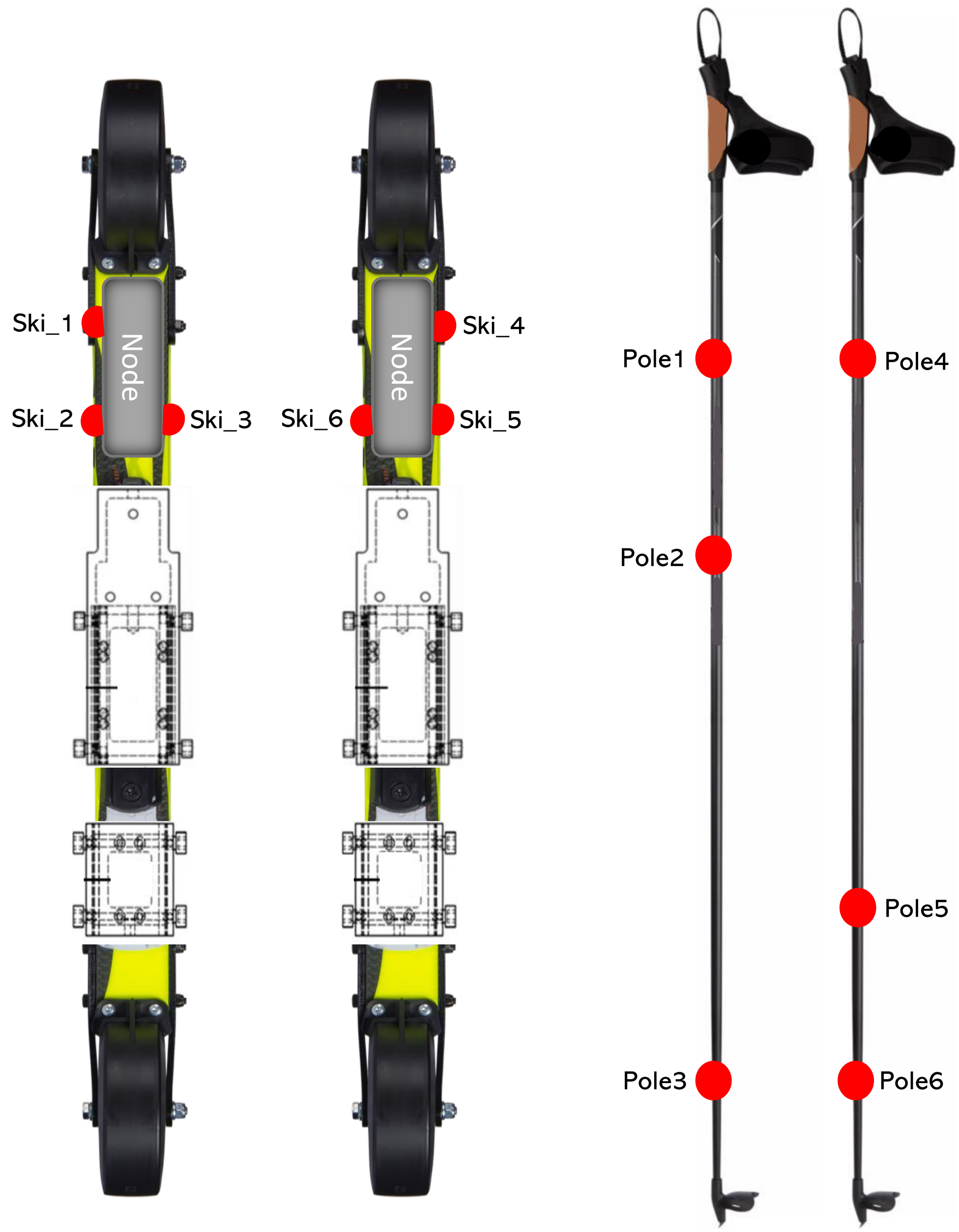

FIGURE 1
Illustration of the marker placement on skis and Poles.

Measurements were performed on a motorized treadmill with a belt surface 2.7 m wide and 3.5 m long (Rodby Innovation AB, Vänge, Sweden). A same pair of roller-skis (Marwe SKATING 620 XC, wheel no. 0, Marwe Oy, Hyvinkää, Finland) were used for both techniques and all participants. Two custom-made pole force sensors (VTT MIKES, Technical Research Centre of Finland Ltd., Kajaani, Finland) were used to measure axial ground reaction force (GRF) from poles at a sample rate of 400 Hz. The pole force sensors were mounted below the pole grip and were calibrated in a certified laboratory for force and mass measurements (VTT MIKES, Technical Research Centre of Finland Ltd., Kajaani, Finland). Two custom-made 2D (vertical and medio-lateral) force measurement bindings (Neuromuscular Research Centre, University of Jyväskylä, Finland) (34) were mounted on the roller-skis to measure the leg forces generated from roller-skis at a sampling rate of 400 Hz. Both pole force sensor and ski measurement bindings have been used in our previous study (35). The total mass of one equipped pole and one equipped roller ski were 202 g and 664 g greater than the normal ones. A trigger signal was sent from the Coachtech online measurement and feedback system (36) (Neuromuscular Research Centre, University of Jyväskylä, Finland) to the motion capture system to mark the start of the force capture. Data from each subject at each incline were collected for at least 30s when the treadmill speed was constant at 10 km/h.

2.4. Data processing

The marker labeling was performed by using NEXUS 2.8.1 software. The raw 3D trajectories of all reflective markers were low-pass filtered (fourth-order, zero-lag, Butterworth filter) with a cut-off frequency of 11.3 Hz (37). Force data were low-pass filtered (eighth-order, zero-lag, Butterworth filter) with a cutoff frequency of 15 Hz (38). Filtering and parameter calculation were performed in MATLAB R2018a (MathWorks, Natick, United States). 10 cycles from each DP technique trail and 5 cycles from each G3 technique trail were analyzed in this current study. For DP technique trails, one cycle was defined as the period between two consecutive right pole plant. For G3 technique, one cycle was defined as the time between consecutive same side ski force minima after ski plant and contained the kicking, overlapping, pure gliding action of both left and right ski and two double poling action from both poles (Figure 2A).

2.4.1. Propulsive force calculation

Forces measured in the force coordinate system were first transformed into the GCS (35). The measured axial pole forces were considered as the ground reaction forces acting along the pole from the tip to the top. The pole forces vector ($\overrightarrow{\mathbf{F}_{\text{pole}}}$) in GCS were calculated as:.

$$\overrightarrow{\mathbf{F}_{\text{pole}}} = \mathrm{F} * \vec{\mathbf{u}}$$

where F was the magnitude of the measured axial pole force and $\vec{\mathbf{u}}$ was the direction vector from the tip to the top of the pole.

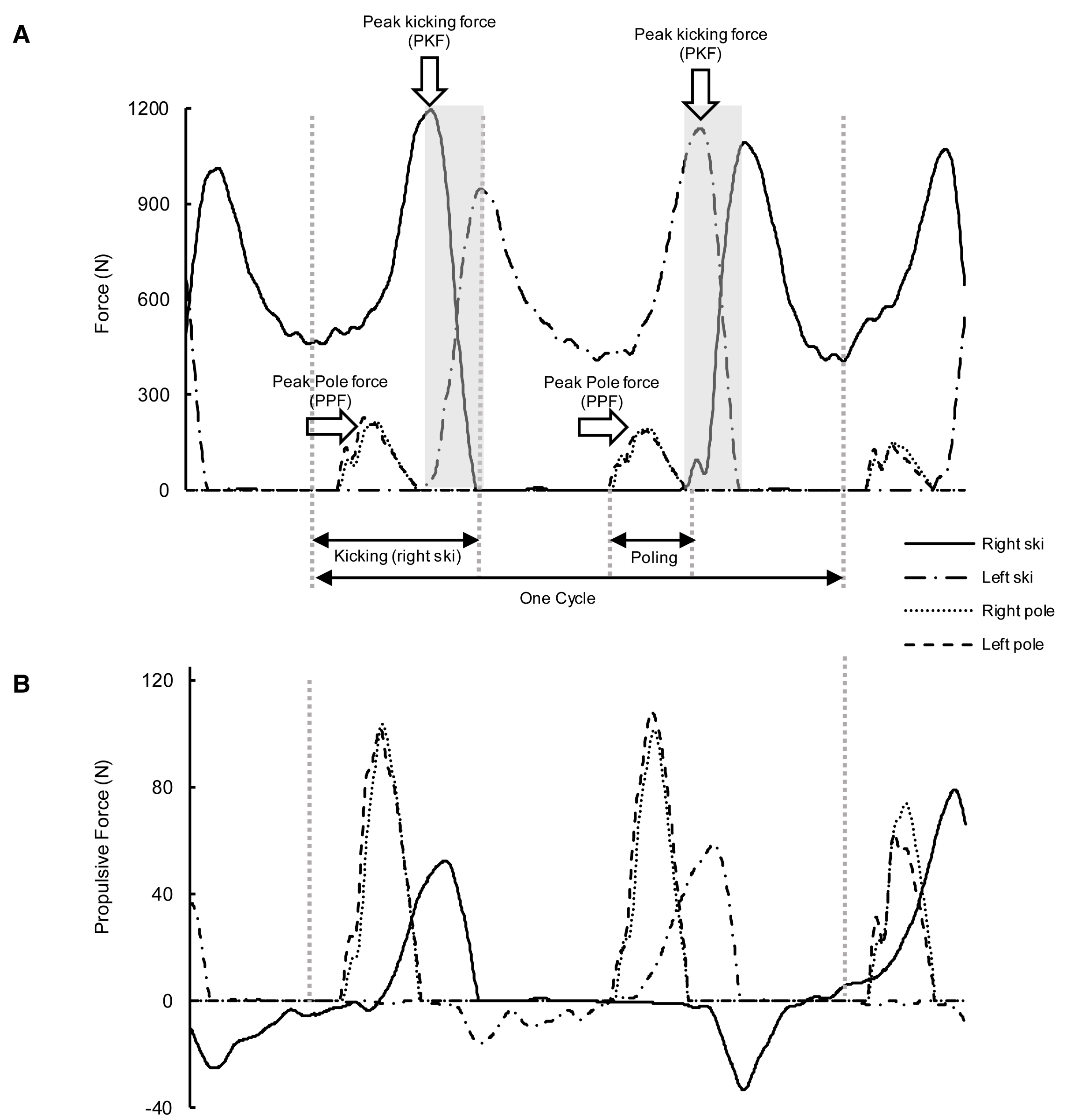

FIGURE 2
Definition of cycle and force variables and time-force curve of propulsive force with G3 technique. A. Definition of cycle and force variables. Areas under the gray shade were the overlap phase. B. Time-force curve of propulsive force from skis and Poles.

The direction vector was defined by using the reflective markers that were attached to the pole. As the measurements were performed at different inclines, the propulsive force component from ski (F_{p_ski}) and from pole (F_{p_pole}) were calculated by:

$$F_{p\_ski} = F_{skiy} * \cos\alpha + F_{skiz} * \sin\alpha$$

$$F_{p\_pole} = F_{pole\_y} * \cos\alpha + F_{pole\_z} * \sin\alpha$$

where α was the incline of the treadmill (3°, 4°, or 5°); F_{pole_y} and F_{pole_z} were the corresponding pole force components in GCS; F_{skiy} and F_{skiz} were the components of GRFs' vector generated from legs in GCS.

2.4.2. Cycle characteristics

The cycle rate (CR) for each technique was the cycles per second (CR = 1/Cycle time, Hz). The cycle length (CL) was defined as the product of cycle time and the speed of the treadmill. In both techniques, the poling time was the ground contact time of the right poles. For G3 technique (Figure 2A), the kicking time of one leg was the time from unweighting minima to the ski release. The overlap time of the legs were defined as the time from one ski plant to the adjacent ski release of the other ski. The relative poling, kicking, and overlap times were calculated for the analysis.

2.4.3. Impulses, effectiveness and contributions of ski and pole forces

The kinetic variables analyzed in this study were similar to those in another study which we concentrated on the effect of changing the treadmill speed. The peak pole force (PPF) for both techniques, and peak kicking force (PKF) for G3 technique were determined by the resultant force from pole and ski respectively (Figure 2A). For both techniques, pole and ski propulsive force impulses as well as ski vertical impulse were calculated. The propulsive force impulse was equal to the cumulative time integral of the propulsive force, restricting the integral to the intervals over which the integrand was positive. The effectiveness index of pole and ski forces was calculated by expressing the pole propulsive impulse and the ski propulsive impulse as a percentage of pole and ski resultant force impulse, respectively (16). The contribution of pole and ski forces in overcoming the total resistance were calculated by expressing the pole and ski propulsive impulse as a percentage of total propulsive impulse (32), respectively. The average cycle propulsive force (ACPF) were determined by dividing the total propulsive impulse by cycle time (16). The power output in overcoming the total resistance in skiing direction was calculated by multiplying the APCF and the speed of the treadmill (m/s) (16).

2.5. Statistical analyses

All the data in this current study were shown as means ± SD. One-way ANOVA with repeated-measures and *Bonferroni post hoc* analysis were conducted to reveal the effect of incline on each characteristic. The effect size (η_p^2) and statistical power were also provided for further evaluation. The level of statistical significance was set at 0.05. All statistical analyses were carried out by using SPSS 22.0 Software (SPSS Inc., Chicago, United States.).

3. Results

In DP technique, the CL (Figure 3A) decreased by 10% as the incline of the treadmill elevated from 3° to 5° ($p < 0.001$). The CR (Figure 3A) and relative poling time (Figure 3B) increased by 13% ($p < 0.001$) and 7% ($p < 0.001$) from 3° to 5°, respectively. From 3° to 5°, PPF increased by 25% ($p < 0.001$, Figure 3C) and the pole propulsive force impulse increased by 29% ($p < 0.001$, Figure 3D). The pole force effectiveness increased by 7% from 3° to 5° ($p < 0.001$, Figure 3E). With DP technique, the ski vertical force impulse decreased with the increasing incline ($p < 0.001$, Figure 3F). The ski propulsive force impulse was small and independent from the incline of the treadmill ($p = 0.284$, Figure 3F). The ACPF and the power output in overcoming the total resistance increased by 46% ($p < 0.001$, Figure 3G) and 45% ($p < 0.001$, Figure 3H) with DP technique, respectively.

With G3 technique, the CL (Figure 4A) decreased by 7% as the incline of the treadmill elevated from 3° to 5° ($p \le 0.001$). The CR (Figure 4A) and the relative poling time (Figure 4B) with G3 technique increased by 9% ($p < 0.001$) and 8% ($p \le 0.008$) from 3° to 5°, respectively. With G3 technique, the relative kicking time (Figure 4C) was independent from the incline ($p = 0.794$). The relative overlap time (Figure 4D) at 3° was greater than relative overlap time at 4° and 5° ($p = 0.101$). From 3° to 5°, the PPF and the PKF increased by 32% ($p < 0.001$, Figure 4E) and 6% with G3 ($p \le 0.037$, Figure 4E) technique, respectively. From 3° to 5°, the pole propulsive force impulse increased by 36% ($p <$ 0.001) with G3 technique (Figure 4F). The ski propulsive force impulse (Figure 4G) at 4° was not different from that at 5° ($p =$ 0.338), but both were greater than the ski propulsive force impulse at 3° ($p < 0.001$). The ski vertical force impulse decreased by 11% from 3° to 5° ($p < 0.001$, Figure 4H). With G3 technique, the enhancements for ACPF were 50% ($p < 0.001$, Figure 5A). The power output in overcoming the total resistance increased by 50% ($p < 0.001$, Figure 5B). The pole force effectiveness (Figure 5C) increased by 5% ($p < 0.001$). The ski force effectiveness (Figure 5C) at 3° was significantly lower than at 4° to 5° ($p < 0.001$, $p < 0.001$). No significant difference on ski force effectiveness between 4° and 5° was found ($p = 0.101$). In G3 technique, around 85% of the total propulsive force was contributed by poles (Figure 5D). The relative contributions of ski and pole forces to overcome the total resistance were affected by the treadmill incline (Figure 5D), but the only difference was between 3° and 4° ($p = 0.003$).

4. Discussion

This study provided the biomechanical characteristics and investigated the relative contribution and effectiveness of ski and pole forces in overcoming the total external resistance

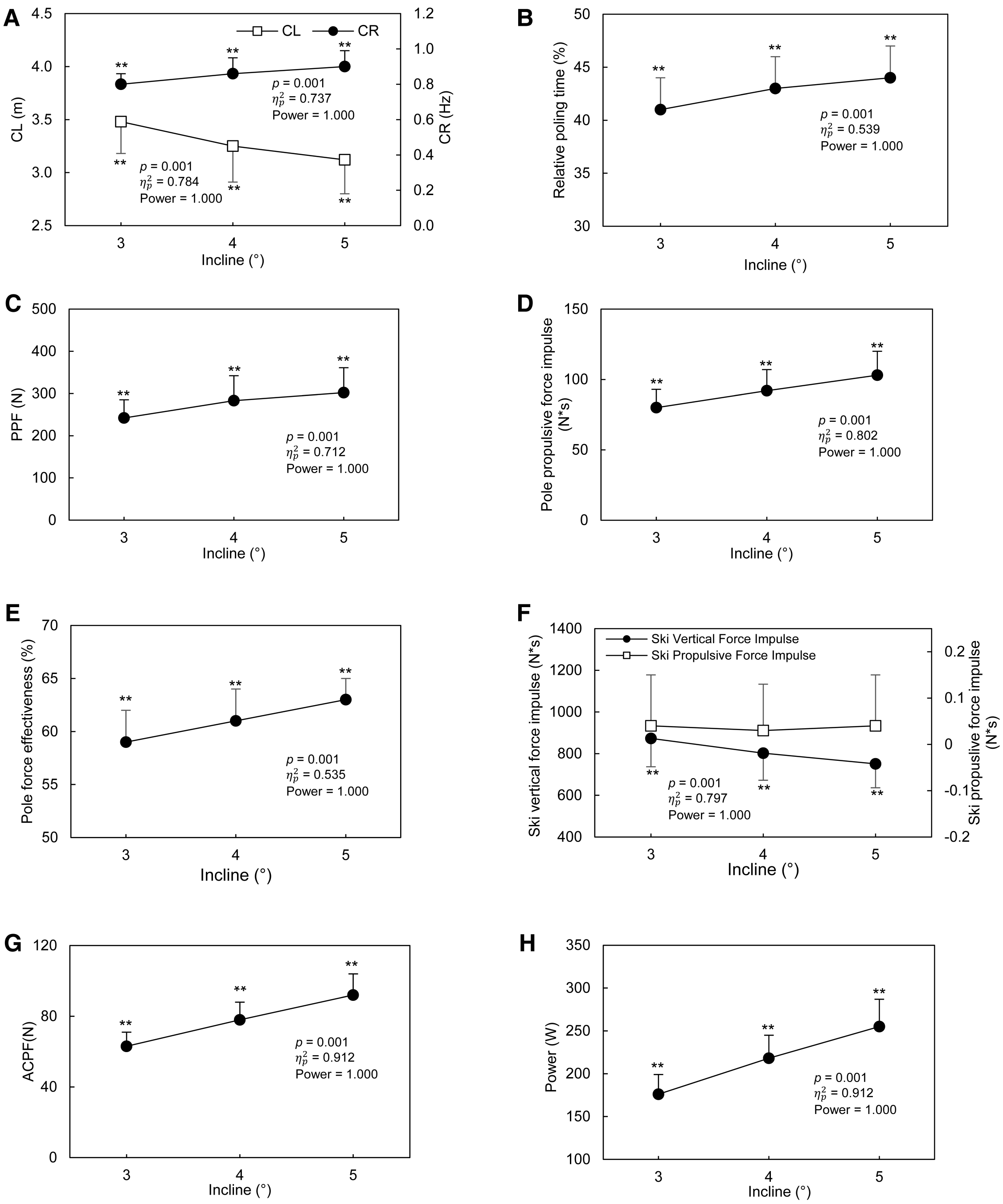

FIGURE 3
Cycle and kinetic characteristics of DP technique at different inclines. A: Cycle length (CL, left axis) and Cycle rate (CR, right axis); B: Relative poling time (%); C: Peak Pole force (PPF); D: Pole propulsive force impulse; E: Pole force effectiveness; F: Ski vertical force impulse (left axis) and Ski propulsive force impulse (right axis), G: Average cycle propulsive force (ACPF), H: Power output in overcoming the total resistance (Power). The data are presented as mean ± SD. The *p* value, η_p^2, and power presented in the figure are from the One-Way ANOVA with repeated measurement test. ***p* < 0.01, compared with all other inclines.

of both DP and G3 techniques at varying moderate uphill inclines. 0.03–0.04 N*s ski propulsive force impulse was found, and the pole force effectiveness increased by 7% from 3° to 5°with DP technique, which support our hypothesis that some propulsive forces from skis could be measured but it would be quite small and pole forces would be more effective at steeper inclines. With G3 technique, 55%–58% of the resultant pole forces was generated to overcome the external resistance and about 85% of the total propulsive force was contributed by poles. Thus, the hypothesis of more contribution from poles and greater pole effectiveness was satisfied.

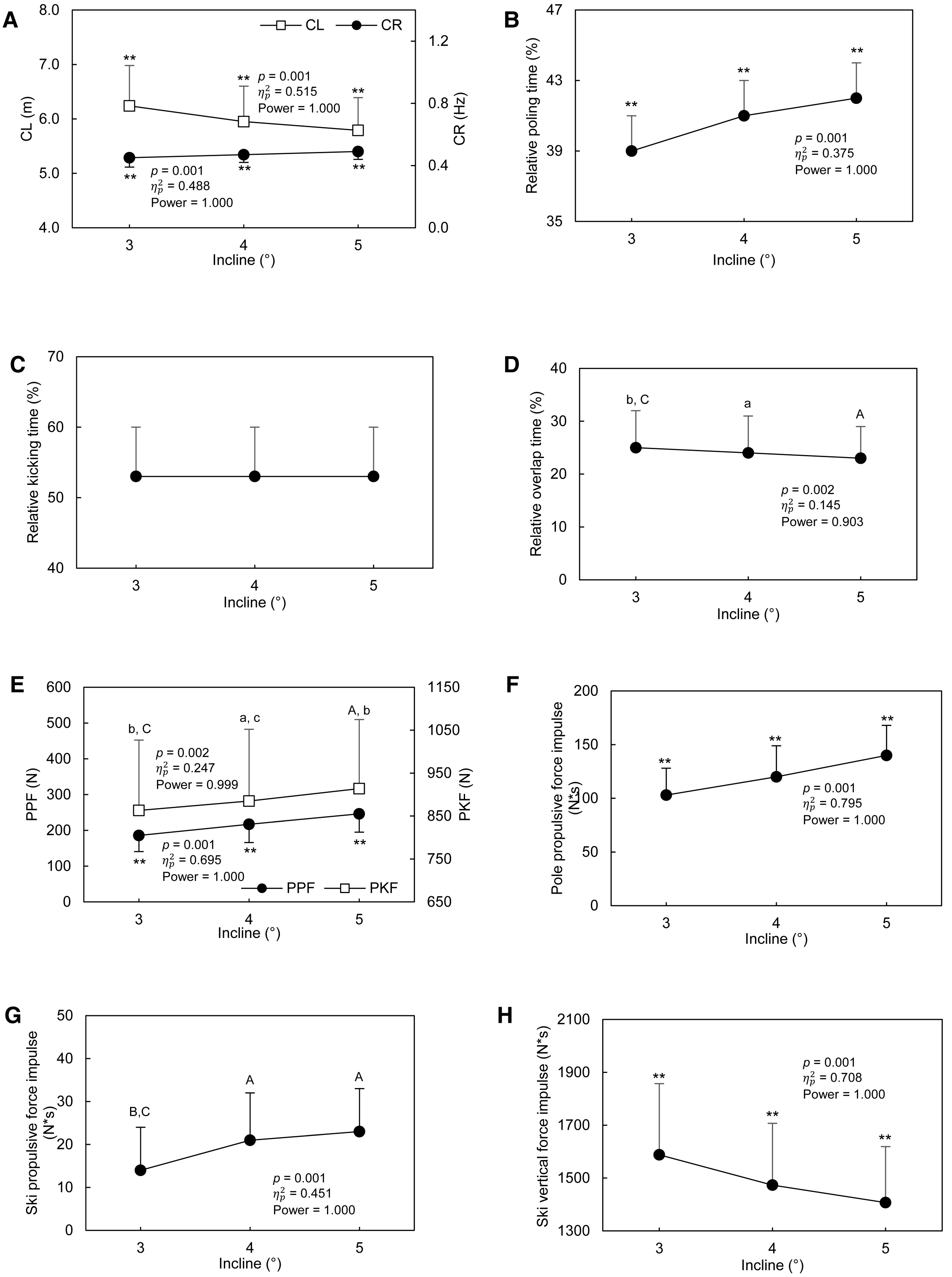

FIGURE 4
Cycle and kinetic characteristics of G3 technique at different inclines. A: Cycle length (CL, left axis) and Cycle rate (CR, right axis); B: Relative poling time (%); C: Relative kicking time (%); D: Relative overlap time (%); E: Peak Pole force (PPF, left axis), Peak kicking force (PKF, right axis); F: Pole propulsive force impulse; G: Ski propulsive force impulse; H: Ski vertical force impulse. The data are presented as mean ± SD. The *p* value, η_p^2, and power presented in the figure are from the One-Way ANOVA with repeated measurement test. $^{**}p < 0.01$, compared with all other inclines. a, A; b, B; c, C, represent different to 3°, 4°, 5°, respectively. a, b, c = $p < 0.05$; A, B, C = $p < 0.01$.

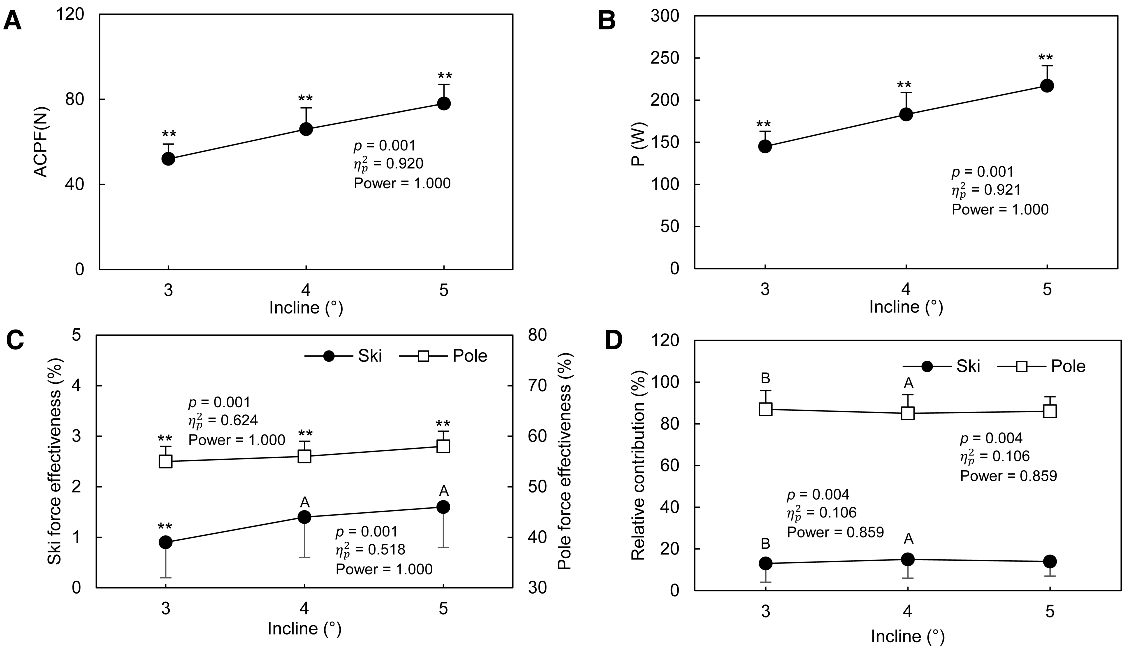

FIGURE 5
Kinetic characteristics of G3 technique at different inclines. A: Average cycle propulsive force (ACPF); B: Power output in overcoming the total resistance (Power); C: Ski force effectiveness (left axis) and Pole force effectiveness (right axis); D: Relative contribution of ski and pole forces in overcoming the total resistance. The data are presented as mean ± SD. The p value, η_p^2, and power presented in the figure are from the One-Way ANOVA with repeated measurement test. **$p < 0.01$, compared with all other inclines. a, A; b, B; c, C, represent different to 3°, 4°, 5°, respectively. a, b, c = $p < 0.05$; A, B, C = $p < 0.01$.

4.1. Cycle characteristics

In response to increases in incline, the CR increased significantly at steeper inclines with both techniques (Figures 3A, 4A). This indicated that shorter time was used by subjects to finish one cycle at steeper inclines. This finding is consistent with previous studies that the CR was higher at steeper inclines with G3 technique (4), and DP technique (19). Since the treadmill speed remained the same at different incline, the CL decreased at steeper inclines with both techniques. Similar finding was found in a previous study that the CL was decreased with both G2 and DP techniques in response to a steeper incline (19). Comparable phenomenon has been demonstrated in uphill running where step length (CL) was decreased and step frequency (CR) was increased with the elevated treadmill incline (39, 40). The adjustment of CL and CR in uphill running was coped with the uphill progression and the available metabolic power (40).

The relative poling time (Figures 3B, 4B) are greater at steeper incline with both technique in this study. Specifically, the time for getting ready for the next pole plant was shorter at steeper incline, and the proportion of cycle for generating pole forces increased with the elevated treadmill incline in both techniques (19). As the G3 technique contains both pole and ski thrusts, the ski movements were analyzed as well. The relative kicking time (Figure 4C) was independent from the incline of the treadmill. This indicated that in response to the increased treadmill incline, the proportion of cycle for generating ski forces would not change.

The relative overlap time (Figure 4D) at 4° and 5° were shorter when compared to that at 3°. The less relative overlap time indicated that the skier may start "seeking ground contact" with the new glide ski later at steeper grade (15). The magnitude of the relative overlap time in this study (23%–25%) was higher than that reported by Ohtonen et al. (15) (around 10%). This difference might be attributed to environmental difference (on snow vs. on treadmill) and athletes' level (a group of elite skiers vs. a group of diverse level skiers). Faster elite skiers may control balance more securely than averaged level skiers (15).

4.2. Forces and impulses

With both techniques, the PPF (Figure 3C and Figure 4E), and pole propulsive force impulse (Figure 3D and Figure 4F) increased continuously up to the steepest incline in this present study. Combined these results with results from cycle characteristics, although less time was used for getting ready for pole plant, greater pole force and pole propulsive force should be reached at steeper incline. These results were consistent with the previous study that in both DP and G2 technique, the force variables from poles were all greater at the steeper grade than the lower grade (19). 0.03–0.04 N*s ski propulsive force impulse was found (Figure 3F) for DP technique in this study. This result supports our hypothesis that with DP technique, we could measure some propulsive force from skis, but it would be quite small. The magnitude of the ski propulsive force impulse was very small and seems to be negligible. Therefore, from overcoming the total resistance point of view, DP technique could be considered as an upper-body movement as indicated by other previous studies (25–27).

Greater ski force and ski propulsive force should also be generated to overcome the increased total resistance at steeper incline with G3 technique, as the PKF and ski propulsive force impulse all increased at steeper incline in this study. However, although participants in this study had similar bodyweight with participants in other previous studies (15, 41), the magnitude of PKF in this study was lower than those in previous studies. The additional weight and height of the roller ski equipped with the force measurement bindings may decrease the usage of legs, thereby greater ski forces could not be reached. In addition, the difference in skiers' level and the skiing intensity level may also be attributed to the difference in PKF.

The gravity component parallel to the treadmill surface increased with the incline (38), thus more forces and greater power output are needed at a steeper grade. Therefore, the ACPF increased continuously with the elevated treadmill incline with both techniques (**Figure 3G** and **Figure 5A**). In response to the elevated treadmill incline, the power output in overcoming the total resistance increased by 45% and 50% with the DP and G3 technique respectively in this study (**Figure 3H** and **Figure 5B**). For DP technique, the propulsive impulse was mainly generated by poles and more pole propulsive force impulse are needed if skier intend to maintain the speed with increasing incline. But with G3 technique, increase the propulsive force generated from both poles and skis are needed. It is also worth remembering that in treadmill conditions skiers do not have to work against wind resistance as is the situation when skiing outside. Especially with higher speed, the wind resistance would have a great influence on propulsive forces (42). Therefore, the results about the magnitude of forces in this study may be different from studies which concentrated on snow skiing (15).

4.3. Effectiveness and contributions of ski and pole forces at different inclines

Effectiveness index has been used as a useful tool to evaluate athlete's overall economy on force production (16). The results of this study support our hypothesis that with DP technique, the effectiveness of pole force in overcoming the total resistance would be greater at steeper inclines than at relative lower inclines. The pole force effectiveness increased by 7% from 3° to 5° with DP technique, indicating that a greater proportion of the resultant force is generated to overcome the total resistance and a higher overall economy on force production. For DP technique, the increase in power output in overcoming the resistance was mainly due to the increase in pole force effectiveness because none of the propulsive force could be obtained by skis.

The results of our study support our hypothesis that pole forces would contribute more to overcome the total resistance and more effective than ski forces at any incline. Our results indicated that the relative contributions of pole forces were 5–6 times greater than the relative contributions of ski forces (**Figure 5D**), and 55%–58% of the resultant pole forces is generated to overcome the external resistance which is greater than the effectiveness of ski force (0.9%–1.6%, **Figure 5C**). A previous study demonstrated that for G3 skating technique, about two thirds of propulsive is due to the pole forces and one-third due to the ski forces (33). The difference between our current study and the previous study (33) may be attributed to the difference in treadmill incline and speed. In addition, the extra weight and height of roller-skis caused by the force measurement bindings may decrease the usage of legs. Therefore, more pole force than ski forces were used in overcoming the total resistance. However, the results of our study do not support our hypothesis that the relative contribution of ski forces to overcome the total resistance would increase at steeper grade. Although the relative contribution from ski and pole forces were affected by the incline of the treadmill, the effects were medium ($\eta_p^2 = 0.106$), and the magnitude of the change did not vary so much. Specifically, increasing the propulsive force generated from both poles and skis are needed at steeper grade but the contribution ratio will not change.

However, what should be noted was that the contribution mentioned in this study were the relative amount of force to overcome the external resistance. The internal work, which is used to move the internal structures and not used to perform work on external objects (43), was not included. A previous study reported that about 37%–46% of the external power was contributed by the trunk and legs in DP technique (38). During the recovery phase of the DP technique or the pure gliding phase in the V2 skating technique, the lower extremity also contributes to repositioning the body, which may help skiers enhance the use of body weight (29, 44) and may increase the forces generated from skis and poles. However, this kind of contribution of lower extremity could not be revealed by the propulsive force. Therefore, only 0.9%–1.6% of the ski forces were generated to overcome the resistance. Results from this study suggests that the role of legs is quite small, but this might be affected by the height and weight of the roller ski and the level of study group. This result needs to be confirmed with higher level athletes and more advanced measurement equipment.

Our study has several limitations. The first limitation is that subjects in this study had varying skiing levels, and we recruited make subjects only. Therefore, future studies with a group of more skilled skiers of both genders will enhance the generality of our conclusion. The measurements of this study were performed in an indoor laboratory and on the treadmill. The lack of wind resistance (42) and the motor and belt of the treadmill (45) may prevent the results of this study from being directly applicable to snow skiing. In addition, the roller skiing equipment used in this study contained force measurement sensors, which are heavier and add extra height compared to the normal ones, may affect the skiing techniques. Future study could reduce the impact of measurement equipment by using portable force measurement roller skis (46) and lighter force measurement poles to help the results more easily transferable to daily roller ski training.

5. Conclusions

The present study provides detailed biomechanical information of DP and G3 techniques at three different uphill inclines. The higher power output in overcoming the total resistance was required to manage skiing at a greater incline. With DP technique this was supplied by greater pole forces and pole force effectiveness, which means that the upper body demands, and technical effectiveness were increasing with incline. This fact plays a role when skiers using DP also to a greater extent in moderate uphill sections like e.g., in "Visma Ski Classic" race events or when skiers are forced to use DP in uphill sections due to worse grip wax conditions for diagonal skiing. With G3 technique, increasing both pole and ski force effectiveness were needed at steeper grade, but the much larger relative contribution of pole forces vs. ski forces in overcoming the total resistance did not change over incline. This underlines the crucial role of external pole work for propulsion during G3 over different terrains while the role of legs may stay more in supporting the body against gravity and repositioning body segments.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary materials, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the University of Jyväskylä. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Conceptualization, SZ, OO, SL, and VL; Data curation, SZ; Formal analysis, SZ; Funding acquisition, SZ and VL; Investigation, SZ, OO, SL, and VL; Methodology, SZ, OO, SL, and VL; Project administration, SZ; Resources, SZ, and OO; Supervision, SZ, OO, SL and VL; Validation, SZ; Visualization, SZ; Writing – original draft, SZ; Writing – review & editing, SZ, OO, SL, and VL. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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.

Publisher's note

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