TRAINING INTENSITY, VOLUME AND RECOVERY DISTRIBUTION AMONG ELITE AND RECREATIONAL ENDURANCE ATHLETES

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TRAINING INTENSITY, VOLUME AND RECOVERY DISTRIBUTION AMONG ELITE AND RECREATIONAL ENDURANCE ATHLETES

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HYPOTHESIS AND THEORY
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The Polarization-Index: A Simple Calculation to Distinguish Polarized From Non-polarized Training Intensity Distributions

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The training intensity distribution (TID) of endurance athletes has retrieved substantial scientific interest since it reflects a vital component of training prescription: (i) the intensity of exercise and its distribution over time are essential components for adaptation to endurance training and (ii) the training volume (at least for most endurance disciplines) is already near or at maximum, so optimization of training procedures including TID have become paramount for success. This paper aims to elaborate the polarization-index (PI) which is calculated as $\log_{10}$(Zone 1/Zone 2*Zone 3*100), where Zones 1–3 refer to aggregated volume (time or distance) spent with low, mid, or high intensity training. PI allows to distinguish between non-polarized and polarized TID using a cut-off > 2.00 a.U. and to quantify the level of a polarized TID. Within this hypothesis paper, examples from the literature illustrating the usefulness of PI-calculation are discussed as well as its limitations. Further it is elucidated how the PI may contribute to a more precise definition of TID descriptors.

Keywords: high-intensity training, high-performance sports, lactate threshold training, endurance training, elite

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INTRODUCTION

The training intensity distribution (TID) of endurance athletes has become an important component of training prescription since (i) the intensity of exercise and its distribution over time are essential components of adaptation to endurance training and (ii) the training volume (at least for most disciplines) is already near or at maximum. Therefore, several optimization procedures have gained scientific interest, including the manipulation of TID, and other components of exercise prescription including exercise duration, volume, frequency, or mode.

To quantify TID, the intensity of exercise is commonly defined according to physiological thresholds and distributed into an "intensity zone-model," of which a three-zone model is predominantly employed for scientific evaluation. Briefly, the intensity of Zone 1 incorporates low-intensity exercise greater than or equal to 50% of maximal oxygen uptake ($\dot{V}O_{2\,max}$) and lower than the intensity corresponding to the first lactate or ventilatory threshold. Exercise prescription in Zone 1 is often termed "basic-endurance" or "low-intensity" exercise. The first and second lactate or ventilatory thresholds define the lower and upper limits of Zone 2, an exercise intensity that is often termed "threshold intensity," or "lactate threshold training." Zone 3 is usually defined as an exercise intensity greater than the second lactate or ventilatory threshold and established as high-intensity interval training near or at maximum $\dot{V}O_{2\,max}$. These training intensities may also be defined by other variables based on blood lactate concentration, percentage of maximal heart rate or $\dot{V}O_{2\,max}$, or subjective ratings like the "Session-RPE". For details see Seiler and Kjerland (2006), Seiler (2010). However, the physiological transitions between training intensities are fluent and the targeted adaptions depend on multiple factors including training volume, TID, health-, and training-status. For detailed reviews see Gibala et al. (2012), Milanović et al. (2015), and MacInnis and Gibala (2016).

Among several TID patterns, four main distributions have been reported and investigated so far, namely the "polarized"-, "high-intensity"-, "pyramidal"-, and "lactate threshold"-TID, which are based on previous definitions (Seiler and Kjerland, 2006; Stöggl and Sperlich, 2015):

- *Polarized TID* consists of elevated percentages of time or distance spent in both high- (Zone 3) and low-intensity exercise (Zone 1) and only a small proportion of training in Zone 2. The polarized TID with its fractions of training volume spent at low-, threshold-, and high-intensity often consists of e.g., 80% of training volume spent in Zone 1, 5% in Zone 2, and 15% in Zone 3 (80-5-15), or 75-5-20, (i.e., 75% within Zone 1, 5% in Zone 2, and 20% in Zone 3), with percentages of Zone 1 greater than Zone 3 *and* Zone 3 always greater than Zone 2.
- *Pyramidal TID* consists of high percentage of training volume spent in Zone 1 and less proportions in Zone 2 and 3. As an example, a pyramidal TID may be quantified as 70-20-10, i.e., 70% within Zone 1, 20% in Zone 2, and 10% in Zone 3.
- *Threshold TID* consists of training volume emphasizing Zone 2. This distribution is frequently established by longer intervals with an intensity between first and second lactate or ventilatory threshold or by continuous exercise intermixed with higher intensities and without a distinct recovery interval. As an example, a threshold TID could be designed as 40-50-10 (i.e., 40% within Zone 1, 50% in Zone 2, and 10% in Zone 3). Notably, a threshold TID, e.g., 50-45-5 (i.e., 50% within Zone 1, 45% in Zone 2, and 5% in Zone 3), may but not necessarily has to be pyramidal (i.e., with decreasing proportions of Zone 2 and Zone 3).
- *High Intensity TID* is a TID with training predominantly performed in Zone 3 and mainly involving interval training. A typical high-intensity TID could be designed as 20-10-70 (i.e., 20% within Zone 1, 10% in Zone 2, and 70% in Zone 3).

Notably, the classification of TIDs to one of the four patterns shown in **Figure 1** maybe ambiguous. Especially the term "polarized" differs substantially between publications (Stöggl and Sperlich, 2015; Plews and Laursen, 2017), nevertheless the polarized TID has received increasing scientific interest since retrospective analysis (Seiler and Kjerland, 2006), and prospective randomized-controlled trials have documented equal (Ingham et al., 2008; Treff et al., 2017) or superior gains in endurance performance (Neal et al., 2013; Stöggl and Sperlich, 2014; Tønnessen et al., 2014) when compared to the pyramidal, threshold, or high-intensity TIDs. "Polarized" TID comprises a variety of fractions of Zone 1-3 and is sometimes even used as a descriptor for pyramidal TIDs (Plews and Laursen, 2017) which are clearly characterized by decreasing proportions of Zone 1, 2, and 3, or for TIDs that do not differentiate between Zone 2 and Zone 3 (Fiskerstrand and Seiler, 2004), thereby violating the aforementioned TID classification. Therefore, the definition of polarized vs. other non-polarized TID is often unclear and sometimes misleading.

For this reason, we would like to present an elaborated concept of our previously published polarization-index (PI) (Treff et al., 2017), which is based on the assumption of two necessary conditions for a polarized TID. (i) a polarized *structure*, where Zone 1 > Zone 3 and Zone 3 > Zone 2 (and consequently Zone 1 > Zone 2) and (ii) a relatively small proportion of Zone 2. The PI aims to distinguish between polarized and non-polarized TID and to quantify the level of a polarized TID. Further, we aim to highlight the PI's usefulness and limitations, thereby contributing to a more precise TID terminology within the scientific literature. Based on studies published between 2009 and 2018 and reported in our previous paper, we want to highlight examples illustrating why we believe the polarization index may be a valuable tool for practical and scientific purposes.

CALCULATION OF THE POLARIZATION-INDEX

The formula for calculation of the PI is based on a three-zone TID-model:

$$Polarization-index\ (a.U.) = \log_{10}(Zone\ 1/Zone\ 2 \times Zone\ 3 * 100) \quad (1)$$

where Zone is the fraction (given percentage/100) of the training volume in Zone 1, 2, and 3.

The PI increases if a high ratio of Zone 1 to Zone 2 is combined with a high percentage of training in Zone 3. The log-transformation of the raw-data establishes a quasi linear function.

If Zone 2 = 0, Eq. 2 avoids zero in the denominator:

$$Polarization-index\ (a.U.) = \log_{10}(Zone\ 1/0.01 \times Zone\ 3 - 0.01 * 100) \quad (2)$$

If Zone 3 = 0, PI is zero per definition.

If Zone 3 > Zone 1 the PI is not valid and must not be calculated (please see discussion for details below).

If PI > 2.00 a.U., the TID is defined as "polarized," with increasing values indicating a higher level of polarization. If PI is ≤ 2.00 a.U., the TID is defined as non-polarized.

JUSTIFICATION OF THE PI-CONCEPT

For a polarized TID we assume (i) a polarized structure and (ii) a relatively small proportion of Zone 2.

Ad (i) For the polarized structure, we agree on the following necessary conditions: a: Zone 1 + Zone 2 +

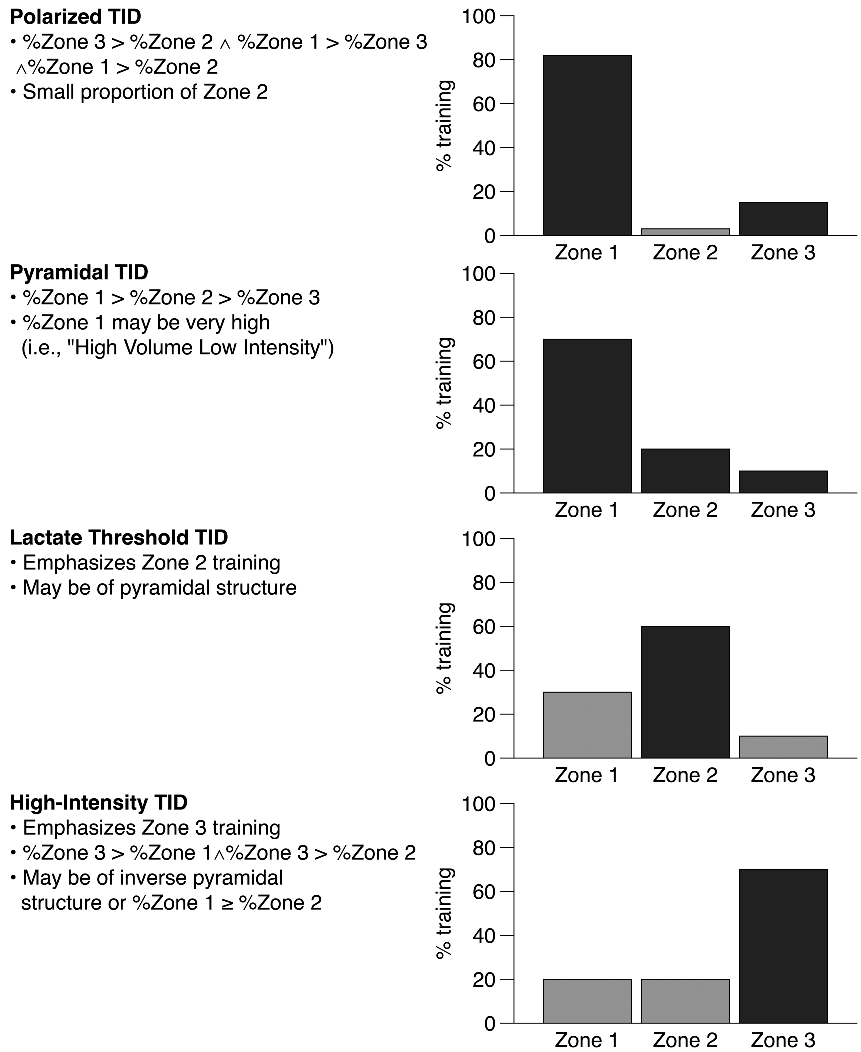

FIGURE 1 | Various training intensity distributions (TID), their schematic proportions, and key characteristics (indicated by black bars). Zones refer to following intensities: Zone 1 (basic endurance), ≥ 50% $\dot{V}O_{2\,max}$ and ≤ first lactate or ventilatory threshold; Zone 2 (lactate threshold), ≥ first and ≤ second lactate or ventilatory threshold; Zone 3 (high intensity), > second lactate or ventilatory threshold.

Zone 3 = 1, b: Zone 3 > Zone 2, c: Zone 1 > Zone 3, and d: Zone 1 > Zone 2. **Figure 2** visualizes these conditions over the range 0–1 (or 0 – 100%) and the colored areas represent the range of fractions where all of these conditions are fulfilled.

Due to these conditions, a PI > 2.00 a.U. is inevitably associated with a polarized structure, because if Zone 2 equals Zone 3 (a TID which does precisely not stand for a polarized structure), the result of Zone 1/Zone 2 × Zone 3 will equal the value of Zone 1, since Zone 2 and Zone 3 will shorten each other, e.g., 0.8/0.2 × 0.2 *100 = 80. Zone 1 approaches the maximal value of 100%, therefore the raw, i.e., not log-transformed PI will approach a value of 100. Since $\log_{10}(100)$ equals 2.00, the PI approaches 2.00 a.U. and cannot exceed a value > 2.00 a.U. if Zone 2 equals Zone 3. Consequently, the percentage of Zone 3 must be higher than Zone 2 to result in a PI > 2.00 a.U. Or, vice versa: If PI > 2.00 a.U., the necessary condition *Zone1 > Zone3 ∧ Zone 3 > Zone 2* will be met in each case for Z1 ≤ 100% (**Figure 2**, green area).

Ad (ii) At the same time the 2.00-threshold can be employed to identify the fulfillment of the second necessary condition for a polarized TID, i.e., comprising of "a relatively small" proportion of Zone 2: If, for example, the percentage of Zone 1 is as low as 60%, a TID of 60-19-21 will result in a PI of 1.82 a.U., thereby clearly below the cut-off and violating the definition of a polarized TID, even though Zone 1 > Zone 3 ∧ Zone 3 > Zone 2 (i.e., the first necessary condition for a polarized TID is *true)*. However, if Zone 2 is lower than ∼ 15% in this example, the PI will be > 2.00 a.U. and consequently, PI calculates 2.05 a.U. in a 60-14-26 distribution.

Of note, with higher percentages of Zone 1 training (e.g., 80%), a Zone 2 percentage lower than 9% will already allow for a polarized TID (e.g., 80-8-12) resulting in a PI of 2.08 a.U.

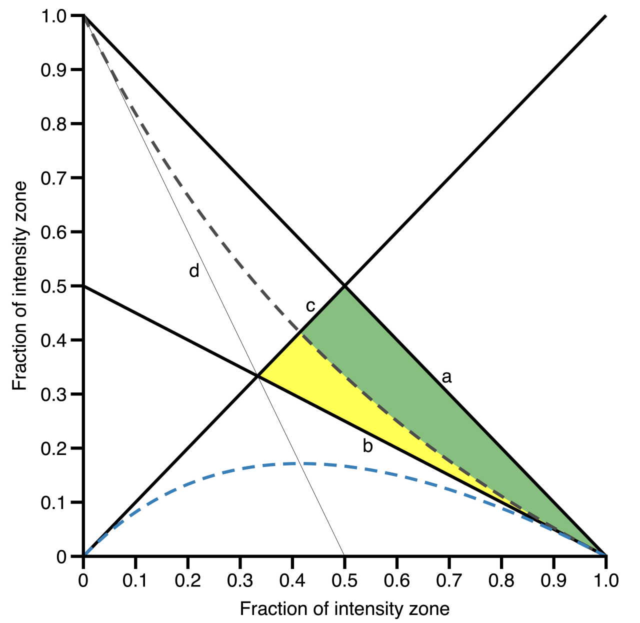

FIGURE 2 | Limits and conditions of the polarization index. Line a indicates the upper limit of Zone 3 for a given (x-axis) fraction of Zone 1 (condition a: Zone 1 + Zone 2 + Zone 3 = 1), line b indicates the lower limit of Zone 3 for a given fraction of Zone 1 (condition b: Zone 3 > Zone 2), line c indicates the upper limit of Zone 3 for a given fraction of Zone 1 (condition c: Zone 1 > Zone 3), and line d indicates the lower limit of Zone 3 for a given fraction of Zone 1 (condition d: Zone 1 > Zone 2). The colored areas represent the range of values where conditions a-d are fulfilled. The gray broken line indicates the limit of Zone 3 for a given fraction of Zone 1 resulting in a polarization-index of 2.00 a.U., i.e., if Zone 3 is higher or lower, polarization-index will result in values higher (green area) or lower than 2.00 a.U. (yellow area), respectively. The broken blue line indicates the upper limit of Zone 2 for a given fraction of Zone 1 to allow for a polarization-index ≥ 2.00 a.U.

This behavior is visualized by the broken blue line in **Figure 2**, indicating the upper limit of Zone 2 allowing for a PI ≥ 2.00 a.U. and the approximation of the broken lines to line b with increasing fractions of Zone 1.

The cut-off > 2.00 a.U. is therefore not arbitrary and clearly providing a benchmark for a polarized structure and an objective (but not physiological) definition of "relatively small" percentages of Zone 2 training in polarized TIDs.

APPLICATION OF THE POLARIZATION INDEX IN TRAINING INTENSITY STUDIES

Table 1 shows several original investigations published between 2009 and 2018 which were discussed in one of our previous papers (Treff et al., 2017), their PI and the employed descriptor.

Five studies of **Table 1** (Ingham et al., 2008; Bourgois et al., 2013; Neal et al., 2013; Stöggl and Sperlich, 2014; Treff et al., 2017) report polarized TIDs according to the PI and the aforementioned definitions i.e., Zone 1 > Zone 2 ∧ Zone 3 > Zone 2 as well as low percentage of Zone 2. One study (Neal et al., 2013) reports a 80-0-20 polarized TID evident with a high PI of 3.18 a.U. In one study (Ingham et al., 2008) the index is even higher, due to lower and greater fractions of Zones 1 and 3, respectively. In three studies the PI was lower compared to the TID of the aforementioned studies (i.e., the level of "polarization" was lessened), due to the greater percentage of Zone 2 (Bourgois et al., 2013; Stöggl and Sperlich, 2014) or lower absolute percentage spent in Zone 3 (Treff et al., 2017).

In two studies of **Table 1** (Neal et al., 2013; Stöggl and Sperlich, 2014) the percentage of training spent in Zone 3 equaled zero. According to the aforementioned definition, the PI amounts to zero and consequently the TID of both studies are not polarized.

In five studies of **Table 1** (Guellich et al., 2009; Plews et al., 2014; Stöggl and Sperlich, 2014; Plews and Laursen, 2017; Treff et al., 2017) the PI varied from 0.71 to 1.80 a.U. representing non-polarized TIDs due to a PI ≤ 2.0 a.U. However, the PI varies reasonably according to the respective contributions of Zone 1, Zone 2, and Zone 3. In detail, the PI is very similar in two examples (Stöggl and Sperlich, 2014; Plews and Laursen, 2017) but clearly higher compared to other studies (Plews et al., 2014; Treff et al., 2017) with a similar fraction of Zone 2, but a nearly threefold higher percentage of Zone 3 at the expense of a lower percentage in Zone 1.

Table 1 also illustrates a special TID variant, as the study by Carnes and Mahoney (2018) represents a TID (74-11-15) in which the percentage of Zone 3 is higher compared to Zone 2, indicating a polarized structure, however the fraction of time spent in Zone 2 is considerably high, thereby not fulfilling the second necessary criterion for a polarized TID (Zone 2 being relatively small), which is mirrored by the PI of 2.00 a.U., indicating a non-, but "nearly"-polarized TID.

CLASSIFICATION AND DETAILED QUANTIFICATION OF TRAINING INTENSITY DISTRIBUTIONS IN THE LITERATURE

As already mentioned, the term "polarized" superficially describes the TIDs within retrospective training analysis and prospective experiments. For example, the "polarized" TIDs of the studies summarized in **Table 1** (Ingham et al., 2008; Bourgois et al., 2013; Neal et al., 2013; Stöggl and Sperlich, 2014) report substantial differences in the fraction of Zone 3 ranging from 6 to 28%. Taking into account that a large body of evidence has revealed that training emphasizing Zone 3 promotes substantial differences in oxygen transport and utilization (Hickson et al., 1977; Milanović et al., 2015), it seems important to know how "polarized" an experiment was in order to judge the level of adaptation in connection with various TIDs, and to allow better comparisons between groups and studies.

Table 1 also provides examples of studies reporting a polarized TID, even though the percentage of Zone 2 is considerably high (≥17%) and proportions of Zone 1 to 3 continuously decrease, thereby clearly indicating a pyramidal TID (Plews et al., 2014). The borderline TID by Carnes and Mahoney (2018) also claims

TABLE 1 | Selected studies in the area training intensity distribution, percentages of three training intensity zones, the resulting polarization-index, and their classification according to the polarization-index and the original publication.

	Authors	Time or distance spent in			Polarization-Index (a.U.)	Classification according to	
		Zone 1 (%)	Zone 2 (%)	Zone 3 (%)		Polarization-Index	Authors
1	Neal et al., 2013	80.0	0.0	20.0	3.18	Polarized	Polarized
2	Ingham et al., 2008	72.0	0.0	28.0	3.29	Polarized	Polarized
3	Stöggl and Sperlich, 2014	68.0	6.0	26.0	2.47	Polarized	Polarized
4	Bourgois et al., 2013	93.1	2.3	4.6	2.27	**Polarized**	**Not classified**
5	Treff et al., 2017	93.0	1.0	6.0	2.75	Polarized	Polarized
6	Neal et al., 2013	57.0	43.0	0.0	0.00	Non-polarized	Non-polarized (LT)
7	Stöggl and Sperlich, 2014	46.0	54.0	0.0	0.00	Non-polarized	Non-polarized (LT)
8	Plews and Laursen, 2017	67.3	30.2	2.5	0.75	Non-polarized	Non-polarized (pyramidal)
9	Stöggl and Sperlich, 2014	83.0	16.0	1.0	0.71	Non-polarized	Non-polarized (HVLT Int)
10	Plews and Laursen, 2017	80.4	17.9	1.8	0.91	**Non-polarized**	**Polarized**
11	Plews et al., 2014	77.3	16.9	5.8	1.42	**Non-polarized**	**Polarized**
12	Treff et al., 2017	94.0	4.0	2.0	1.67	Non-polarized	Non-polarized (pyramidal)
13	Guellich et al., 2009	95.0	3.0	2.0	1.80	Non-polarized	Non-polarized
14	Carnes and Mahoney, 2018	74.0	11.0	15.0	2.00	**Non-polarized**	**Polarized**
15	Stöggl and Sperlich, 2014	43.0	0.0	57.0	n.a.	–	HIT

LT, lactate threshold training; Hi HVLT, high volume low intensity; HIT, high intensity training. Bold letters indicate that classification according to polarization-index differs from classification in the original publication.

to have employed a “polarized” TID. In each of these studies, the application of the PI would provide a more precise and objective classification of the respective TIDs.

APPLICATION OF THE POLARIZATION-INDEX IN TRAINING MONITORING AND ANALYSIS

Figure 3 is an example retrieved from a previous paper of our group, illustrating the practical application of the PI in a scientific study simultaneously illustrating the practical application of the PI for training monitoring, and analysis with two groups of rowers performing either a pyramidal (PI = 1.70 a.U.) or a polarized TID (PI = 2.70 a.U.) (Treff et al., 2017). As in similar training studies, the TIDs differed significantly between groups, but at the individual level, the training was quite heterogenous. The PI therefore might allow for a more precise analysis of training outcomes taking into account the actual individual TID. Further, the PI can easily be integrated into standard training monitoring software.

However, some rules should be followed when interpreting the PI:

As shown before, very small differences between Zone 2 and Zone 3 will allow for a PI $\geq$ 2.00 a.U. if percentage of Zone 1 is high. Therefore, the PI is practically useful within reasonable and accepted limits for Zone 1 in polarized TIDs, being approximately 70–90% (Stöggl and Sperlich, 2014). Also, a given TID with, for example, 15 h/week training will affect performance differently to the same TID with a volume of, for example, 25 h/week. Therefore, interpretation of changes in performance in relation to a given TID (as illustrated in **Figure 3**) is only justified when other important variables of training (e.g., training volume, frequency, or training modalities) are clamped, or are at least similar between subjects or within subject. In this case, we would like to emphasize that the PI as an algorithm assists in discriminating between various TIDs, but we discourage the interpretation as a surrogate for training load. For example, a PI of 2.00 a.U. may result out of two substantially different TIDs, e.g., 90-5-5 and 74-13-13. As explained above, and from a biological and empirical perspective, these two training regimes, unlike TID, will result in different central and peripheral adaptations and will affect performance differently, even if applied in a theoretically perfect model, i.e., two identical subjects. It is also worth to mention, that the quality of training data and a reliable and valid allocation of the intensities is crucial for analysis. Finally, successful training is not only a quantitatively but also strongly qualitatively

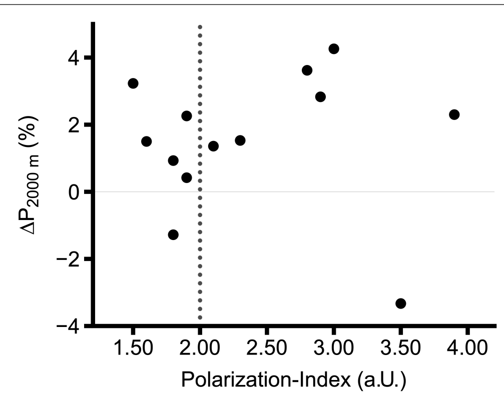

FIGURE 3 | Percentage change of average power in 2000 m rowing ergometer test ($P_{2000\ m}$) in internationally competing rowers. Vertical dashed line represents the cut-off between non-polarized ($\leq$ 2.00 a.U.) and polarized (> 2.00 a.U.) TIDs. Figure adapted from Treff et al. (2017).

determined intervention and not reflected by the PI or other quantitative training variables.

LIMITATIONS

Despite the practical usefulness, the PI has some limitations that warrant a brief discussion. Even though the PI provides an objective cut-off to distinguish polarized from non-polarized distributions, it does not allow the differentiation of sub-types of the non-polarized TID structures (for example, lactate-threshold vs. high-intensity TID) and values between 0 and 2.00 must not be interpreted in terms of more or less polarized distributions. Furthermore, from a theoretical perspective, it appears inappropriate to replace 0.00% in Zone 2 by e.g., 1.00% to avoid zero in the denominator (Eq. 2). However, from a practical perspective, it is virtually impossible to achieve high intensities (i.e., Zone 3), without some fraction of time spent in Zone 2. Therefore, this limitation appears to be practically irrelevant. Finally, the PI is a statistical measure that increases data density and thereby - like every index - leads to a loss of detailed information.

CONCLUSION

The application of the PI represents an algorithm to distinguish distinctively between polarized and non-polarized TIDs and to judge the level of polarization. As shown, the PI has the potential to reduce the ambiguity regarding the classification of TIDs in the current literature and is easily applicable in any training monitoring software. Since the PI also allows intra-individual assessment of polarization, we aim to stimulate researchers to re-evaluate their existing data retrospectively in order to investigate the response or non-response to various TIDs. In addition, we encourage future training experiments to state the level of polarization allowing for more detailed comparison between studies.

AUTHOR CONTRIBUTIONS

GT drafted the manuscript. GT, KW, MS, JS, and BS contributed substantially to the manuscript.

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EDITORIAL
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Editorial: Training Intensity, Volume and Recovery Distribution Among Elite and Recreational Endurance Athletes

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Editorial on the Research Topic

Training Intensity, Volume and Recovery Distribution Among Elite and Recreational Endurance Athletes

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Stimulated by the debate among endurance athletes and coaches of whether an optimal training intensity distribution (TID) exists, we recently reviewed the literature of studies dealing with TID in various sports (Stöggl and Sperlich, 2015; Stöggl, 2018). Our research identified numerous intensity zone models for quantifying TID. Among all TID models, a three zone-based TID seems widely applied among the literature. Within this model "Zone 1" represents low-intensity exercise below first lactate or ventilatory threshold. "Zone 2" exhibits accumulated levels of blood lactate between the first and second lactate or ventilatory threshold. "Zone 3" represents high-intensity exercise above the second lactate or ventilatory threshold.

Based on our (Stöggl and Sperlich, 2015) and other findings (e.g., Billat et al., 2001; Seiler and Kjerland, 2006; Sandbakk et al., 2011; Tonnessen et al., 2014) various TID exist including a so-called polarized (Zone1 > Zone3 > Zone 2) (Fiskerstrand and Seiler, 2004; Seiler and Kjerland, 2006) or pyramidal TID (Zone1 > Zone 2 > Zone 3) (Stöggl and Sperlich, 2015), depending on the discipline.

Since controlled and prospective training experiments are time consuming, complex, requiring both the coaches and athletes to adhere to scientific rules and methods we were motivated to stimulate this research topic to gain broader and deeper insights in TIDs during preparation, pre-competition, and competition phases in different endurance disciplines and performance levels. Ultimately, we wanted to identify TIDs demonstrating greater efficacy than others and highlight research gaps in an effort to direct future scientific investigations.

Based on the numerous contributions to this research topic we have learned the following:

METHOD FOR TRAINING QUANTIFICATION

Based on Manunzio et al.'s analysis of 6-months preparation analysis of a 2nd place Race Across America finisher team ($n = 4$ athletes) the TID may vary depending on the method employed. Retrospective power data analysis based on the 3-zone model revealed a pyramidal TID (Zone 1: 63%; Zone: 28%; Zone 3: 9%) when including coasting phases (i.e., power output below 50% of power at maximum lactate steady state, MLSS). The same data set without coasting phases reflected a threshold TID with a greater Zone 2 emphasis (48/39/13%). The amount of training time <50% of MLSS was shown to be remarkably high with 28% (104 h) of total training time.

POWER-DURATION RELATIONSHIP

In their concept (Hofmann and Tschakert) describe the relationship between power/velocity and the corresponding maximal duration/distance. Based on the power-duration relationship their concept may allow coaches or athletes to individually define the intensity and duration of an exercise session.

DISCIPLINE SPECIFIC TID

In their attempt to answer the question of whether the training for marathon is harder than for an Ironman, Esteve-Lanao et al. employed the Objective Load Scale (ECOs) training load quantification method. For Ironman, the highest associations between performance and training were found with total training time and % of time in zone 1 (<Aerobic Threshold), while no association was found for total ECOs or amount of training in Zone 3 (>anaerobic threshold). Marathon performance was related to both total training time and total training load. Further, it was associated with total amount of Zone 1 plus the accumulation of any variable related to Zone 3 training. For both, Ironman and Marathon, the amount of Zone 2 training was associated with poorer competition performance. Ironman athletes trained more (more than twice total time, and >1/3 of training load) however less hard (e.g., training load per training hour) than marathon athletes. The differences in performance related to TID emphasizes the need for discipline specific TID analysis.

BLOCKED TID

The study of McGawley et al. investigated the performance, stress, recovery and physiological effects to nine session of high intensity interval training (HIIT) evenly distributed over 3-weeks vs. nine HIIT sessions within 1 week with no further HIIT in the other 2 weeks. The authors showed that well-trained junior cross-country skiers are able to complete nine HIT sessions within 1 week without compromising total work done or experiencing greater stress or reduced recovery over a 3-weeks polarized microcycle. Although, both 3-weeks TIDs improved performance (i.e., 600-m roller skiing time trial) and various hormonal and muscle markers, the findings do not suggest that block-distributed HIIT is superior to evenly distributed HIIT within a 3-week period.

RELATION BETWEEN TRAINING LOAD AND RECOVERY-STRESS STATE

Collette et al. aimed (i) to analyze the individual time-delayed linear effect relationship between training load and recovery-stress state with single-case time series methods and (ii) to monitor the acute recovery-stress state of high-performance swimmers over a 17-weeks macro cycle. The Acute Recovery and Stress Scale (ARSS), was shown to be a suitable tool for monitoring the acute recovery-stress state in swimming, especially with respect to the physical and overall scales, while the mental and emotional scales were not. Further, the authors recommend using the sRPE method, with respect to volume (km) rather than training time (h), to monitor the internal training load in swimmers.

GROSS EFFICIENCY AND TID

Skovereng et al. investigated the possible effects of initial performance, gross efficiency and VO_{2peak} on subsequent adaptations to a 12-weeks endurance training including HIIT (24 supervised HIIT sessions, 3/ and 1/weeks during recovery week in combination with *ad libitum* low intensity training) in competitive cyclists. In general, this training concept led to an increase in VO_{2peak}, peak and mean power output during a 40 min time trial, while gross efficiency decreased. Initial performance demonstrated only small to moderate effects on training response.

SPRINT INTERVAL TRAINING (SIT) WITH DIFFERENT INTERVAL RECOVERY

In a 2-weeks experiment (6 sessions) by Olek et al. physically active males performed a series of 10-s sprints separated by either 1- or 4-min of recovery. The number of sprints progressed from four to six separated by 1–2 d rest. VO_{2max}, citrate synthase activity and Wingate anaerobic test results improved similarly in both groups. Only end power output increased by 10.8% in the group with 1-min recovery. The two SIT protocols induced metabolic adaptations over a short period of time, and reduced recovery between SIT bouts may attenuate fatigue during maximal exercise.

SEVEN-DAY RUNNING BLOCK ON AORTIC BLOOD PRESSURE

Tomoto et al. investigated the impact of a condensed 7-day running camp on aortic blood pressure in two groups of collegiate endurance runners (i.e., one group accomplishing the weekly training target: 31 km/d vs. one group not accomplishing the weekly training target 13 km/d). Pulse wave analysis revealed elevated aortic blood pressure in the group with 31 km/d while this was not the case in the group with distinctly lower training volume and intensity.

TID IN ELITE FEMALE CROSS-COUNTRY SKIERS

The case study by Solli et al. presents the TID of the world's most successful female cross-country skier. Following a 12-years nonlinear increase in training load of approximately 80% (522–940 h/years) from the age of 20–35, the annual training volume during the five consecutive most successful years stabilized at 937 ± 25 h, distributed across 543 ± 9 sessions. She displayed a polarized TID, but to a lesser extent during the latter part of her career (i.e., 88/22/20% at the age of 20–27 years vs. 92/3/5% at the age of 28–35 years). While the total time in

Zone-1 and 2 reduced from general preparation, to specific preparation and competition phase, Zone 3 increased from 4.1 to 9.2 sessions/month.

UPPER-BODY EXERCISE

Børve et al. investigated the effects of replacing two HIT sessions with either combined upper-body muscular endurance training and running intervals (mixed endurance group) or only running intervals. Both concepts were performed as pyramidal TID. The 6-weeks mixed training approach increased both muscular endurance and maximal strength in a simulated double poling exercise and 1,000-m double poling performance following a 50-min submaximal trial with no changes in the endurance group. Specific upper-body muscular endurance training thus seems as a promising training model to optimize performance in well-trained cross-country skiers.

OFF-TRAINING ANALYSIS AND TID

Not only the training stimulus itself but also other off-training stimuli may explain variation in adaptation among individuals (Sperlich and Holmberg), therefore it seems strange that the aspect of off-training behavior is mostly not considered within TID analysis. The study by Sperlich et al. demonstrated that national elite rowers demonstrate a substantial sedentary off-training behavior of more than 11.5 h/day. The question about the effects of off-training physical activity during recovery and the long-term performance development is open to future research.

TID IN ELITE ROWERS

Treff et al. analyzed different TID (polarized vs. pyramidal TID with similar amount of Zone 1 training) in national elite rowers. Based on their analysis both TID showed similar gains in performance. The polarized compared to the pyramidal TID seemed not to be superior, possibly due to a very similar percentage of Zone 1 training.

TID AND ACUTE HEART RATE RECOVERY AND ANAEROBIC POWER

Stöggl and Björklund explored whether four TID (9 weeks of HIIT vs. polarized TID vs. threshold vs. high volume low intensity) induced different responses on neuromuscular status, anaerobic capacity/power and acute heart rate recovery (HRR) in well-trained endurance athletes. They concluded that only a training regime that includes a significant amount of HIIT improves the neuromuscular status, anaerobic power and the acute HRR in well-trained endurance athletes.

TID AND IMMUNE FUNCTION

Born et al. hypothesized that nine session of HIIT in 3 weeks would increase levels of salivary cortisol, reduce Immunoglobin-A secretion rate and impair mood thereby demonstrating marked psycho-immunological stress-response and compromised mucosal immune function compared to long slow distance (LSD) running. Based on their data the authors concluded that the increased Immunoglobin-A secretion rate with HIIT indicates no compromised mucosal immune function compared to LSD. Further, this shows the functional adaptation of the mucosal immune system in response to the increased stress and training load of nine sessions of HIIT.

Although the research topic broadened our understanding of various aspects of TID in elite and recreational sports, there are still various research question subject to future investigation, including the following (the authors are aware that this list is not exhaustive):

i) Currently most TIDs are defined as a certain percentage of training time or session within an intensity zone. However, this approach does not allow to judge the density of sessions nor the timing between sessions. Furthermore, depending on the sport strength training maybe included but differs substantially in intensity but no TID model, at least to our knowledge, has implemented this matter into a TID model.
ii) It remains unclear why (i) endurance athletes exercise a large proportion at low-intensity although endurance competitions are usually executed at higher intensity and (ii) why so many different TID may exist.
iii) The long-term effects of TIDs (e.g., inverse polarized or HIIT) and potential shifting of TID within a season or between seasons are still not totally understood.
iv) We believe that the development of wearable technology should further ease and improve our understanding of different TID (e.g., the interaction of internal-external load, stress, fatigue and recovery process).

At this point we'd like to thank the authors for their contribution and we hope this research topic will not only provide new insights and viewpoints about the issues of TID in endurance training, but will also stimulate novel thoughts, experiments, and further advances in this field of research.

AUTHOR CONTRIBUTIONS

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

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Relation Between Training Load and Recovery-Stress State in High-Performance Swimming

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Background: The relation between training load, especially internal load, and the recovery-stress state is of central importance for avoiding negative adaptations in high-performance sports like swimming. The aim of this study was to analyze the individual time-delayed linear effect relationship between training load and recovery-stress state with single case time series methods and to monitor the acute recovery-stress state of high-performance swimmers in an economical and multidimensional manner over a macro cycle. The Acute Recovery and Stress Scale (ARSS) was used for daily monitoring of the recovery-stress state. The methods session-RPE (sRPE) and acute:chronic workload-ratio (ACWR) were used to compare different methods for quantifying the internal training load with regard to their interrelationship with the recovery-stress state.

Methods: Internal load and recovery-stress state of five highly trained female swimmers [with a training frequency of 13.6 ± 0.8 sessions per week and specializing in sprint (50 and 100 m), middle-distance (200 and 400 m), or long distance (800 and 1,500 m) events] were daily documented over 17 weeks. Two different types of sRPE were applied: RPE*duration ($sRPE^{h}$) and RPE*volume ($sRPE^{km}$). Subsequently, we calculated the ratios $ACWR^{h}$ and $ACWR^{km}$ (sRPE last week: 4-week exponentially weighted moving average). The recovery-stress state was measured by using the ARSS, consisting of eight scales, four of which are related to recovery [Physical Performance Capability (PPC), Mental Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR)], and four to stress [Muscular Stress (MS), Lack of Activation (LA), Negative Emotional State (NES), Overall Stress (OS)]. To examine the relation between training load and recovery-stress state a cross correlation (CCC) was conducted with $sRPE^{h}$, $sRPE^{km}$, $ACWR^{h}$, and $ACWR^{km}$ as lead and the eight ARSS-scales as lag variables.

Results: A large variation of training load can be observed in the individual week-to-week fluctuations whereby the single fluctuations can significantly differ from the overall mean of the group. The range also shows that the CCC individually reaches values above 0.3, especially with $sRPE^{km}$ as lead variable. Overall, there is a large range with

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significant differences between the recovery and stress dimensions of the ARSS and between the training load methods, with $sRPE^{km}$ having the largest span (*Range* = 1.16). High inter-individual differences between the athletes lie in strength and direction of the correlation $|0.66| \leq CCC \geq |-0.50|$. The time delayed effects (lags 0–7) are highly individual, however, clear patterns can be observed.

Conclusion: The ARSS, especially the physical and overall-related scales (PPC, OR, MS, OS), is a suitable tool for monitoring the acute recovery-stress state in swimmers. MPC, EB, LA, and NES are less affected by training induced changes. Comparably high CCC and Ranges result from the four internal load methods, whereby sRPE, especially $sRPE^{km}$, shows a stronger relation to recovery-stress state than ACWR. Based on these results and the individual differences in terms of time delay in training response, we recommend for swimming to use sRPE to monitor the internal training load and to use the ARSS, with a focus at the physical and overall-scales, to monitor the recovery-stress state.

Keywords: monitoring, training, recovery-stress state, internal load, session RPE, ACWR, time series analysis, individual case

INTRODUCTION

Analyzing internal and external training loads has become a critical issue in elite sport practice and research. In this regard, monitoring the athletes internal training load is essential for understanding whether athletes are positively adapting to their training program. This implements an understanding of the individual's responses to training, assessing fatigue and the associated need for recovery, in order to minimize the risk of non-functional overreaching, injury and illness (Bourdon et al., 2017; Kellmann and Beckmann, 2018; Kellmann et al., 2018). In high-performance sports like swimming an individual monitoring of the training load and the recovery-stress state for the prevention of negative adaptations is recommended (Foster et al., 1999; Smith, 2003; Lambert and Mujika, 2013; Collette, 2016; Soligard et al., 2016; Crowcroft et al., 2017).

Referring to Bourdon et al. (2017) the measures of *training load* can be categorized as either internal or external, where external training loads are objective measures of the work performed by the athlete (e.g., speed, acceleration, volume, . . .). On the other hand, internal training load is defined as the relative physiological and psychological stressors imposed on the athlete during training or competition. Various methods for measuring internal load exist, such as rating of perceived exertion (RPE), session rating of perceived exertion (sRPE), training impulse (TRIMP), heart-rate indices, blood lactate, oxygen uptake and/or psychological scales and questionnaires (Bourdon et al., 2017). At present, especially the 'sRPE' (Foster et al., 1999) as well as the 'acute:chronic-workload ratio' (ACWR) (Gabbett, 2016; Hulin et al., 2016) methods are being discussed, whereas sRPE has been extensively investigated and seems to be a valid tool for measuring internal training load in a variety of sport (Foster et al., 2001; Herman et al., 2006; Seiler and Kjerland, 2006; Borresen and Lambert, 2008), especially in swimming (Wallace et al., 2008, 2009; Toubekis et al., 2013). Nagle et al. (2015) modified the method of Foster by using the volume (km) instead of the duration for the calculation. It is assumed that in endurance sports such as swimming, volume has a greater impact on the recovery-stress state than duration. A validation study in which both methods are compared is not yet available. The ACWR is a simplification of the fitness-fatigue model of Banister et al. (1975) and it was recently reported to provide valid information regarding injury risk in team sports (Hulin et al., 2016; Gabbett, 2016; Bowen et al., 2017; Murray et al., 2017b). It is therefore reasonable to conclude that ACWR also provides valid information regarding the impact of the internal load on *recovery-stress state*.

The recovery-stress state is based on the individual's ability to utilize resources necessary for recovery in order to compensate stressful situations and activities (Nässi et al., 2017). Stress and recovery appear to be complex, intertwined processes that should be viewed from different perspectives such as time frames and/or contexts, and even multiple processes (Kenttä and Hassmén, 1998; Kellmann and Kallus, 2001; Kellmann and Beckmann, 2018). In high-performance sport self-report measures via questionnaires represent the most common form for monitoring the athlete's recovery-stress state (Nässi et al., 2017) and for this purpose, several valid and reliable instruments are available, e.g., the Profile of Mood States (POMS) (McNair et al., 1971) or the Recovery-Stress-Questionnaire for Sport (RESTQ-Sport) (Kellmann and Kallus, 2001, 2016) are the most frequently used instruments (Saw et al., 2016, 2017). However, both instruments do not examine the acute recovery-stress state in a multidimensional manner. The main criterion for POMS is the predominantly negative orientation of the questionnaire (Martin et al., 2000; Ziemainz and Peters, 2010) and that it has been developed for the assessment of mood (Hitzschke et al., 2016). However, recovery-stress state and mood are regarded as separate psychological constructs (Mäestu et al., 2005). The RESTQ-Sport includes 76 items and is therefore not suitable for a weekly or daily use (Kellmann, 2000). Additionally, recovery and stress state are evaluated over the last 3 days and therefore the questionnaire does not indicate the acute ('here right now') condition of the athlete (Kölling et al., 2015). Meeusen et al. (2013) point out that for effective load monitoring a shorter questionnaire or instrument is needed which responds sensitively to the current state of recovery and stress. As a result, Kellmann et al. (2016) developed the Acute Recovery and Stress Scale (ARSS) to assess and monitor the acute multidimensional recovery and stress state, that considers not only the physical, but also the emotional and psychological recovery or stress. The ARSS can be applied on a daily basis for training monitoring in elite sports (Hitzschke et al., 2017). Several laboratory and field studies in swimming (Collette, 2016), cycling (Hammes et al., 2016), rowing (Kölling et al., 2016), tennis (Wiewelhove et al., 2016), football (Pelka et al., 2017) or strength and high-intensity interval training (Raeder et al., 2016) showed the practicability and suitability to changes of the training stimuli of the ARSS. These studies showed that daily changes as well as indications for a general trend of the recovery-stress state in different training phases will be displayed.

Several studies have investigated the relationship between training load and well-being or recovery-stress state, with an increase in 'stress' and reduction in 'recovery' after intensive training, respectively, higher training load in comparison to normal training load. In addition, a reduction in stress scales and increase in recovery scales were also observed following a taper phase. Furthermore, the results show a high variability and indicate a high degree of individuality (Morgan et al., 1987; Berglund and Safstrom, 1994; Adams and Kirkby, 2001; O'Connor and Puetz, 2005; Coutts et al., 2007; Kellmann, 2010; Bresciani et al., 2011; Brink et al., 2012; Laux et al., 2015).

In high-performance sport, there is a high degree of individuality in terms of training loads and training adaptation (Collette, 2016; Julian et al., 2017). In addition, the recovery-stress structure is characterized by high individuality (Bouchard and Rankinen, 2001; Hautala et al., 2006; Hecksteden et al., 2015, 2017; Schimpchen et al., 2017).

However, the above-mentioned studies show a number of shortcomings: (a) mostly the focus was to compare group values, no single case study performed before; (b) typically pre–post study design was applied so that the process cannot be observed; (c) the studies usually comprise short periods or specific training phases (e.g., taper-phase, training camps); (d) the recovery-stress state was evaluated over a time period (e.g., over 3-days with the RESTQ-Sport), only one-dimensionally (e.g., RPE) or the mood is measured (e.g., POMS).

Considering these critical points, the aim of the present study was

(a) to analyze the individual time-delayed linear effect relationship between training load and recovery-stress state with single case time series methods (bivariate cross-correlations),
(b) to monitor the acute recovery-stress state of high-performance swimmers in an economical and multidimensional manner over a long period or different training periods (macro cycle)
(c) to compare different methods for quantifying the internal training load with regard to their interrelationship with the recovery-stress state,
(d) to detect differences in the relationship between internal load and the two states 'recovery' and 'stress' determined by using the ARSS.

MATERIALS AND METHODS

Participants

Five female high-performance swimmers (S1–S5, mean ± *SD*: age: 21 ± 2.8 years, body mass: 60.1 ± 6.5 kg, height: 1.72 ± 0.1 m, best Fédération Internationale de Natation (2014) points in main event as percentage of world record 72.8 ± 7.9%) monitored daily over 17 weeks. All participants were well-trained athletes, accustomed to a training frequency of more than thirteen sessions per week (13.6 ± 0.8), including pool and athletic sessions. Specialized in sprint (50 and 100 m), middle-distance (200 and 400 m) or long distance (800 and 1,500 m) events.

The study received approval from the Ruhr-Universität Bochum, Faculty of Psychology, Ethics Committee. All participants gave their written informed consent to participate in the study which was conducted in accordance with the Declaration of Helsinki.

Design

Athletes were monitored over a 17-week macrocycle (tw) which included different mesocycles and periodization phases, as well as one or two main competitions [German Championships (tw 9)/German Youth Championships (tw 16)]. Within these macrocycle a 16 days training camp was included at end of week three. The recovery-stress state was recorded every morning using the ARSS. Additionally, internal training load using sRPE was documented after every training session. In order to provide as much error-free documentation as possible, the training load was recorded by both the athletes themselves and the coach. The athletes were instructed to complete the ARSS questionnaire every morning before the first training session. The questionnaire was provided on an online platform[1] and was filled out using the athlete's smartphone or tablet. The compliance was high with data only missing for S1, S2 (1 day each/0.8%) and S5 (6 days/5.0%).

For calculations the following parameters were individually collected: duration of every training session (min); volume (km); sRPE; ARSS. **Figure 1** shows a systematic overview of the study design as well as the collected or calculated parameters.

Training Load

Two different methods of sRPE were used to quantify the internal training load and based on the sRPE values the 'acute:chronic workload ratios' (ACWR) were calculated (**Table 1**).

Session RPE

As described by Foster et al. (2001) within 30 min after every training session participants were given standard instructions for

[1] www.soscisurvey.de

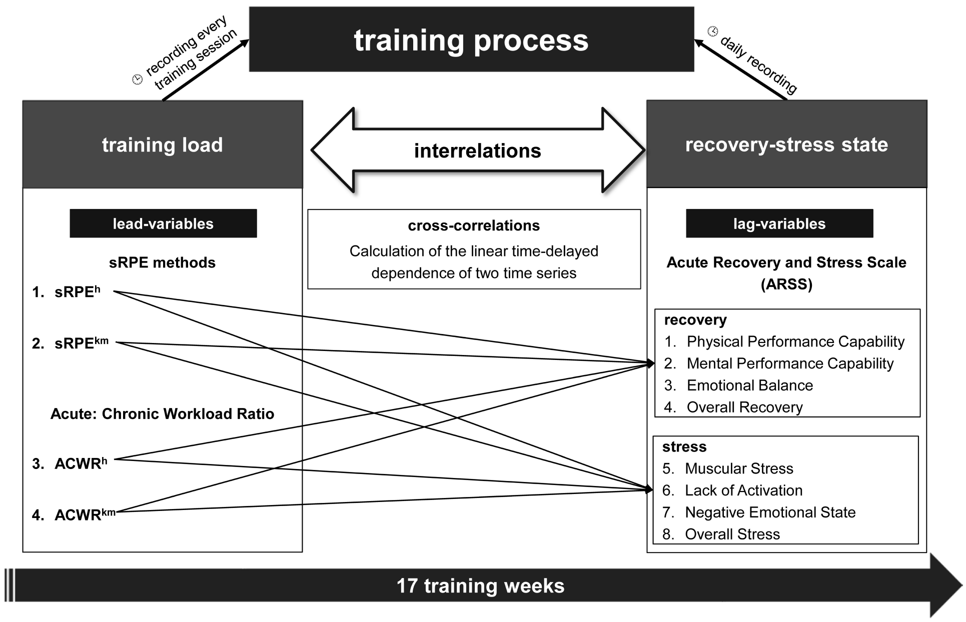

FIGURE 1 | Systematic overview of the study design and the collected or calculated parameters. Cross-correlations were calculated for every of the four lead-variables with every scale of the ARSS as lag-variable. $sRPE^h$ = RPE*duration (min); $sRPE^{km}$ = RPE*volume (km); $ACWR^h$ = $sRPE^h$ last week/$sRPE^h$ 4-week exponentially weighted moving average; $ACWR^{km}$ = $sRPE^{km}$ last week/$sRPE^{km}$ 4-week exponentially weighted moving average.

overall RPE and were asked to report based on the degree of whole body heaviness and strain experienced during the exercise task using a 11-point scale (based on the CR-10 scale by Borg, 1982), with 0 and 10 corresponding to 'rest' and 'maximal,' respectively.

For the first method, *sRPE*^{h}, the training load was calculated by multiplying the 0–10 rating by the total session duration (in min) and expressed in arbitrary units (Foster et al., 2001). Weekly $sRPE^h$ training load was calculated for each athlete individually by summing the $sRPE^h$ training loads for all training sessions.

The second method, *sRPE*^{km}, differs only in a modified calculation for the sRPE-method by using volume (in km) instead of duration (in min) (Nagle et al., 2015). Weekly $sRPE^{km}$ training load scores were calculated for each athlete individually by summing the $sRPE^{km}$ training loads for all training sessions. To consider dryland workouts the duration of the session was converted to volume based on Mujika et al. (1996) (60-min dryland session equals 2 km of swimming).

TABLE 1 | Overview of the various calculation formulas for the methods of training load quantification.

Method	Calculation formula	Unit
$sRPE^h$	= RPE*duration (min)	AU
$ACWR^h$	= $sRPE^h$ last week/$sRPE^h$ 4-week exponentially weighted moving average	AU
$sRPE^{km}$	= RPE*volume (km)	AU
$ACWR^{km}$	= $sRPE^{km}$ last week/$sRPE^h$ 4-week exponentially weighted moving average	AU

sRPE, session rating of perceived exertion; ACWR, acute:chronic workload ratio; AU, arbitrary units.

Acute:Chronic Workload Ratio

The training load (sRPE) of 1 week is defined as the acute load and the chronic training load represent the exponentially weighted moving average (EWMA) of the load in the four previous weeks of training (Nielsen et al., 2014; Gabbett, 2016; Murray et al., 2017a).

As described by Williams et al. (2016) and Murray et al. (2017a), the EWMA is calculated as follows:

$$EWMA_{today} = sRPE_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$$

and λ_a is calculated as:

$$\lambda_q = 2/(N + 1)$$

Where *N* is the time decay constant with 1 week (7 days) for acute and 4 weeks (28 days) for chronic workloads. For the ratio the *EWMA* ACWR value of acute workload was divided by the *EWMA* ACWR value of chronic workload. To begin the EWMA calculation, the first observation in the series is arbitrarily recorded as the first workload value in the series (Murray et al., 2017a).

Comparing the acute training load to the chronic training load as a ratio provides an index of athlete preparedness and fatigue (Gabbett, 2016). The ACWR was divided into the following ranges: very low $\leq$ 0.49, low 0.5–0.99, moderate 1.0–1.49, high 1.50–1.99, and very high 2.0 (Murray et al., 2017a). As such an 'acute:chronic workload ratio' between 0.8 and 1.3 was considered the 'sweet spot,' while ratios $\geq$ 1.5 represent the 'danger zone' with an increased risk of injury (Blanch and Gabbett, 2016; Gabbett, 2016). The 'acute:chronic load ratio' calculated with training loads based on the sRPE^{h}- ($ACWR^{h}$) and sRPE^{km}-Method ($ACWR^{km}$) is shown in **Table 1**.

Acute Recovery and Stress Scale

The ARSS consists of a total of 32 adjectives describing the physical, emotional, mental, and general aspects of recovery and stress based on a 7-point Likert scale from 0 (does not apply at all) to 6 (fully applies) (Kellmann et al., 2016). The adjectives are summarized in eight scales, of which four are related to stress, and four to recovery. The recovery-related scales are: *Physical Performance Capability (PPC), Mental Performance Capability (MPC), Emotional Balance (EB)*, and *Overall Recovery (OR)*. The stress-related scales are: *Muscular Stress (MS), Lack of Activation (LA), Negative Emotional State (NES)*, and *Overall Stress (OS)* (Hitzschke et al., 2017). All scales of the German ARSS showed satisfactory internal consistency (range between $\alpha = 0.84$ and $\alpha = 0.96$) and a good model fit for both the recovery (RMSEA = 0.07, CFI = 0.97, SRMR = 0.04) and stress (RMSEA = 0.09, CFI = 0.94, SRMR = 0.05) factors (Kellmann et al., 2016). Nässi et al. (2017) reported the psychometric properties of the English version of the ARSS.

Statistical Analyses

The time-series analysis is designed to investigate the time-lagged effects of several variables, in which the correlations between the training loads and the recovery-stress state are investigated using bivariate cross-correlations. In other words, the linear dependence on the time delay of two time series is calculated here (Schmitz, 2000). For this purpose, two time series are shifted against each other by π-times, resulting in a lead variable and a lag variable. The direction of the displacement, e.g., the variable which is the lead and the lag variable (Schmitz, 1996) is important. As lead variables, the sRPE and ACWR values are set in this study in order to examine the time-delayed effects of the training on the recovery-stress state in terms of the eight scales of the ARSS as lag variables. This means that for every athlete 32 cross-correlations (**Figure 1**) with $n = 119$ data points (days) were calculated. A significant correlation can be interpreted in the sense of a co-determination of the lag variable by the lead variable (Schmitz, 2000). According to Maiwald and Rogge (2005), significant cross-correlations are found for physiological variables and ordinally scaled self-estimates when their absolute value is greater than CCC ≥ 0.2. Due to the method of cross-correlation, only the maximum significant cross-correlation coefficients (max. CCC) with the associated time delay (lag) are of interest for further evaluation. In order to avoid the possibility of false inconsistencies, a 'pre-whitening' (data transformation into 'White Noise') of the time series is deliberately dispensed with, which is why the strengths of the cross-correlation coefficients can only be interpreted with extreme caution, especially in the case of interindividual comparisons (Schmitz, 1996). The IBM© SPSS© Statistics 23 software package was used to perform the complex statistical calculations. The cross-correlation logs have been calculated for seven lags (7 days) and show the corresponding 95% confidence intervals (e.g., **Figure 2**). Since the time-series analyzes are very sensitive to erroneous data, the few missing data are estimated. The estimated value was determined by calculating the mean value 2 days before and after the data gap. The calculation of the mean values of the cross-correlation coefficients implemented the Fischer-Z transformations (Bortz and Schuster, 2010).

RESULTS

Training Load

Total mean training volume was 833.7 $\pm$ 14.1 km with a mean maximum of 89.0 km in tw 4 and a minimum of 30.8 km in tw 7 (**Figure 3A**).

Total mean *sRPE*^{km}-load was 3888.1 $\pm$ 72.4 au, with a maximum (440.5 au) in tw 4 and a minimum (123.6 au) in tw 7 (**Figure 3B**).

The *sRPE*^{h} values also show a similar distribution as the sRPE^{km} values, with the peak loads striking in particular during the training weeks with competitions (tw 6, tw 9, tw 16). Mean sRPE^{h}-training load was 114996 $\pm$ 2630 au (**Figure 3C**).

Overall, a large variation can be observed in the individual week-to-week fluctuations whereby the single fluctuations can significantly differ from the overall mean plus/minus the standard deviation of the group (**Figures 3A–C**).

Thus, the individual maximum for volume (91.0 km in tw 4) and sRPE^{h} (2110 au in tw 7) can be seen for athlete S1, while athlete S3 has the maximum for sRPE^{km} (18390 au in tw 6). The individual minimum for volume (9.1 km in tw 13) and sRPE^{km} (55.3 au in tw 13) has also athlete S1, while S5 shows the minimum for sRPE^{h} (2110 au in tw 7) (**Figures 3A–C**).

Figure 4 shows the 'ACWR' based on the sRPE^{h}- (**Figure 4A**) and the sRPE^{km}-values (**Figure 4B**). Only the $ACWR^{h}$ curves of Athletes S1, S4, and S5 are in the 'very high' (>2.0) range and these are only short-term peaks over a day. Except for S1 all athletes have a peak in the range of 1.5–1.99 (high) or >2.0 in training week 9 in which the German Championships took place. In comparison, the values in the training camp (end of tw 3 to tw 5) are all in moderate range (1.0–1.49). In the $ACWR^{km}$ curves only S1 shows a peak in the very high range and this, as with $ACWR^{h}$, in training week 13. In addition, peaks in the high range can only be seen S1 and S5. Overall, the curves of $ACWR^{km}$ are smoother compared to $ACWR^{h}$ and predominantly in the low (0.5–0.99) to moderate (1.0–1.49) range.

Cross-Correlation

Only the maximum significant CCC is considered for further analysis due to methodological reasons of the cross-correlation (see above). **Table 2** shows the mean (*MCCC*) and the ranges of the CCC between the sRPE and ACWR values as lead variables and the dimensions of the ARSS, separated into recovery and stress, as lag variables. The highest *MCCC* are observed for *MS* with sRPE^{h} (*MCCC* = 0.41), respectively, sRPE^{km} (*MCCC* = 0.51) and for *OS* with sRPE^{km} (*MCCC* = 0.39). The range in **Table 2** also shows that the CCC individually reaches values above 0.3 in other dimensions, especially with sRPE^{km} as lead variable. Overall, there is a large range with significant

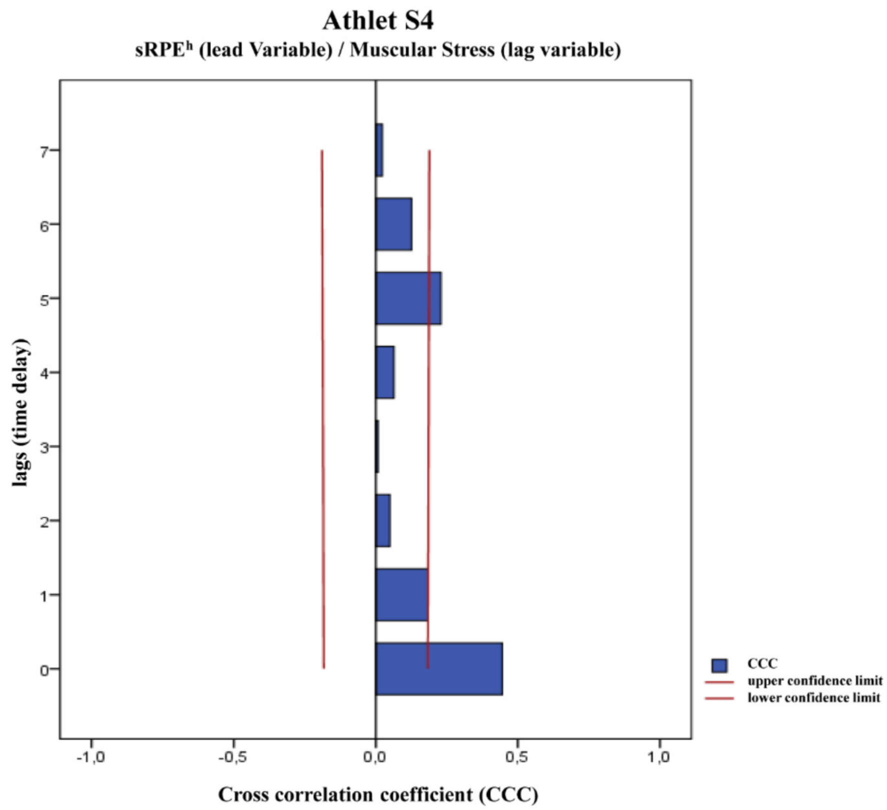

FIGURE 2 | Example of a cross-correlation plot for Athlete S4 with $sRPE^h$ as lead-variable and the ARSS-Dimension *Emotional Balance* as lag-variable.

differences between the recovery and stress dimensions of the ARSS, and between the training load methods, with $sRPE^{km}$ having the largest span of *Range* = 1.16. Furthermore, it is noticeable that for $sRPE^{km}$, $ACWR^{km}$, and $ACWR^h$ for the dimensions *MPC, EB, LA,* and *NES* ranges from negative to positive CCC, and thus different effective directions are present. Therefore, **Figures 5**, **6** show the level and effective direction of the individual CCC, as well as the time delay, based on their lags. Contrary directions of action show for athletes S1, S3, and S4 but for different lead variables and dimensions, whereby only the mental and emotional dimensions (*MPC, EB, LA*, *NES*) are shown. S3 (*MPC* CCC = 0.22, *EB* CCC = 0.22, *NES* CCC = −0.26) and S4 (*EB* CCC = 0.30, *NES* CCC = −0.24) show for $sRPE^{km}$ contrary effective directions, for $ACWR^h$ only S1 (*NES* CCC = −0.19) and for $ACWR^{km}$ S1 (*EB* CCC = 0.24, *LA* CCC = −0.18, *NES* CCC = −0.25), and S4 (*MPC* CCC = 0.23, *LA* CCC = −0.21). This also shows that there are more significant CCC values with the stress dimensions than with the recovery dimensions and in some cases, there are even considerably higher CCC.

In addition to the magnitude of the relationship between training load and recovery-stress state, from a training control perspective the time-delay of the relation is of interest. Our findings show high inter-individual as well as intra-individual differences of the time delayed effects, concerning the athletes and each dimension of the ARSS with lag 0 to 6 for $sRPE^h$, $ACWR^{km}$, $ACWR^h$, and 0 to 7 for $sRPE^{km}$.

To make the time-delayed effects comparable with each other, an individual profile using a network diagram was created for each athlete and for all four lead variables. **Figure 7** shows the individual profiles in terms of time-delayed interaction for the recovery (*PPC, MPC, EB, OR)* and stress dimensions (*MS, LA, NES, OS)* of the ARSS with $sRPE^h$, $sRPE^{km}$, $ACWR^h$, and $ACWR^{km}$ as lead variables. If $sRPE^h$ and $ACWR^h$ are not taken into account only once for S3 and $sRPE^{km}$ for S4, three basic tread patterns can be distinguished. The athletes S1 ($sRPE^h$, $ACWR^h$), S3 ($ACWR^{km}$), and S5 ($sRPE^h$, $sRPE^{km}$, $ACWR^h$, $ACWR^{km}$) react very quickly or directly with lag 0 or lag 1 (or a single maximum lag 3 for S5) in dimensions where significant correlations on the individual training load exist (Profile 1). Profile 2 shows only a small deviation; one or two dimensions react with a significantly larger time delay (lag 4 to 6). For S2 (*NES, LA*) and S3 (*MPC, EB*) these are only mental or emotional-related scales, for S1 only the overall scales (*OR, OS*) and for S4 (*PPC, MS, LA, OS*) both occurs. Profile 3 is distinctly different from the other two profiles, as all dimensions except for *MS* (lag 0) react explicitly later with lag 5 to 7. It can be noticed that for all athletes and all load methods only for *MS*, the time-delayed effect is always between 0 and 2. The only exception here is athlete S4 for $ACWR^h$ with lag 5.

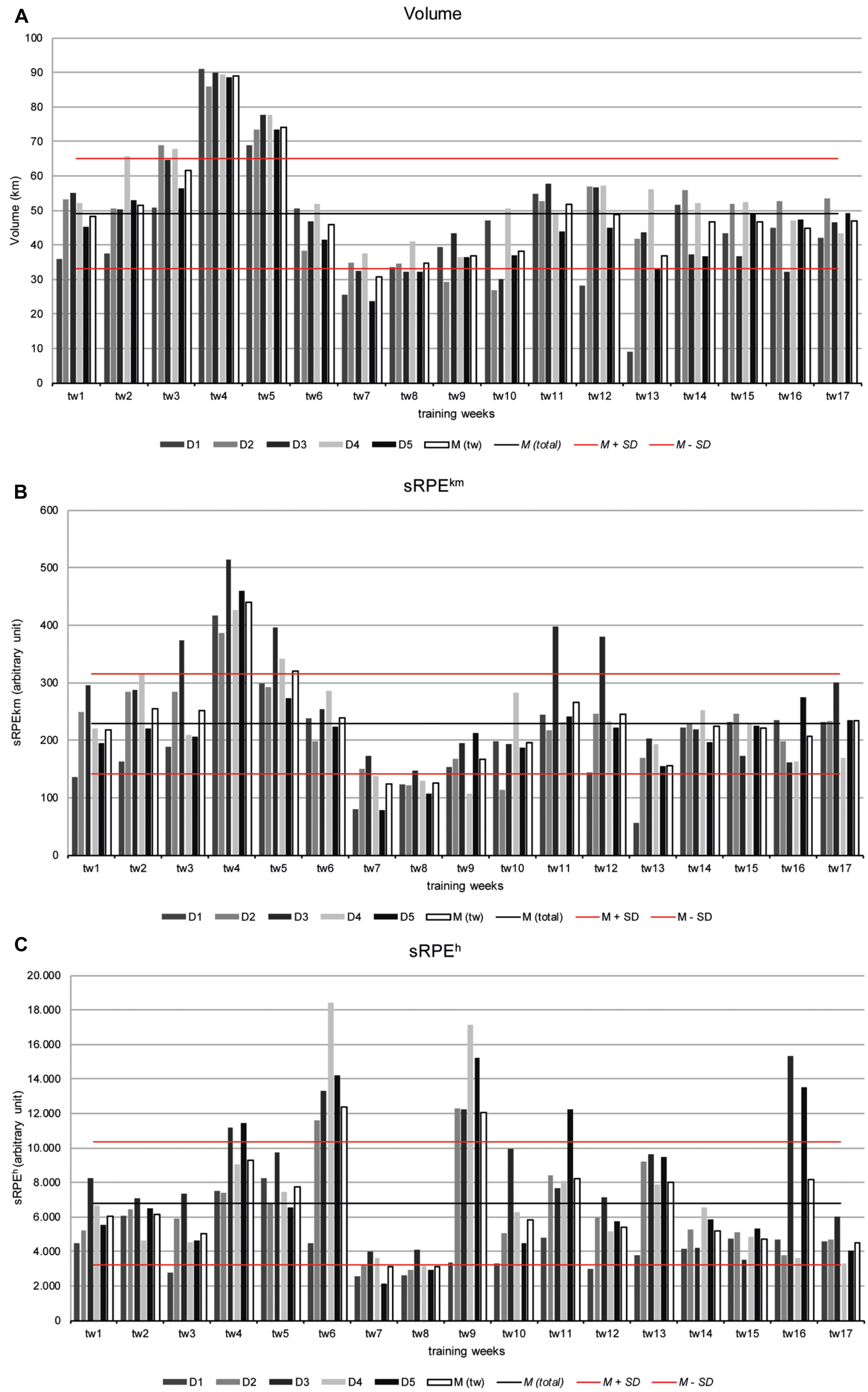

FIGURE 3 | Training load **(A)** volume (km) **(B)** $sRPE^{km}$ and **(C)** $sRPE^{h}$ over 17 training weeks of the athletes S1–S5 as well as the mean values [*M* (tw)]. To estimate the changes from week to week, the total mean value [*M* (total)] as well as plus/minus a standard deviation (*M* ± *SD*) for reference are indicated.

DISCUSSION

The time-delayed linear effect relationship, which has been calculated according to the time series analysis using bivariate cross-correlations between the individual training load and the dimensions of the ARSS, confirm the theoretical assumption that the interactions between training load and the recovery-stress state is characterized with high inter- and intra-individual differences. It also reaffirms the idea that recovery and stress should be explored using a multi-level

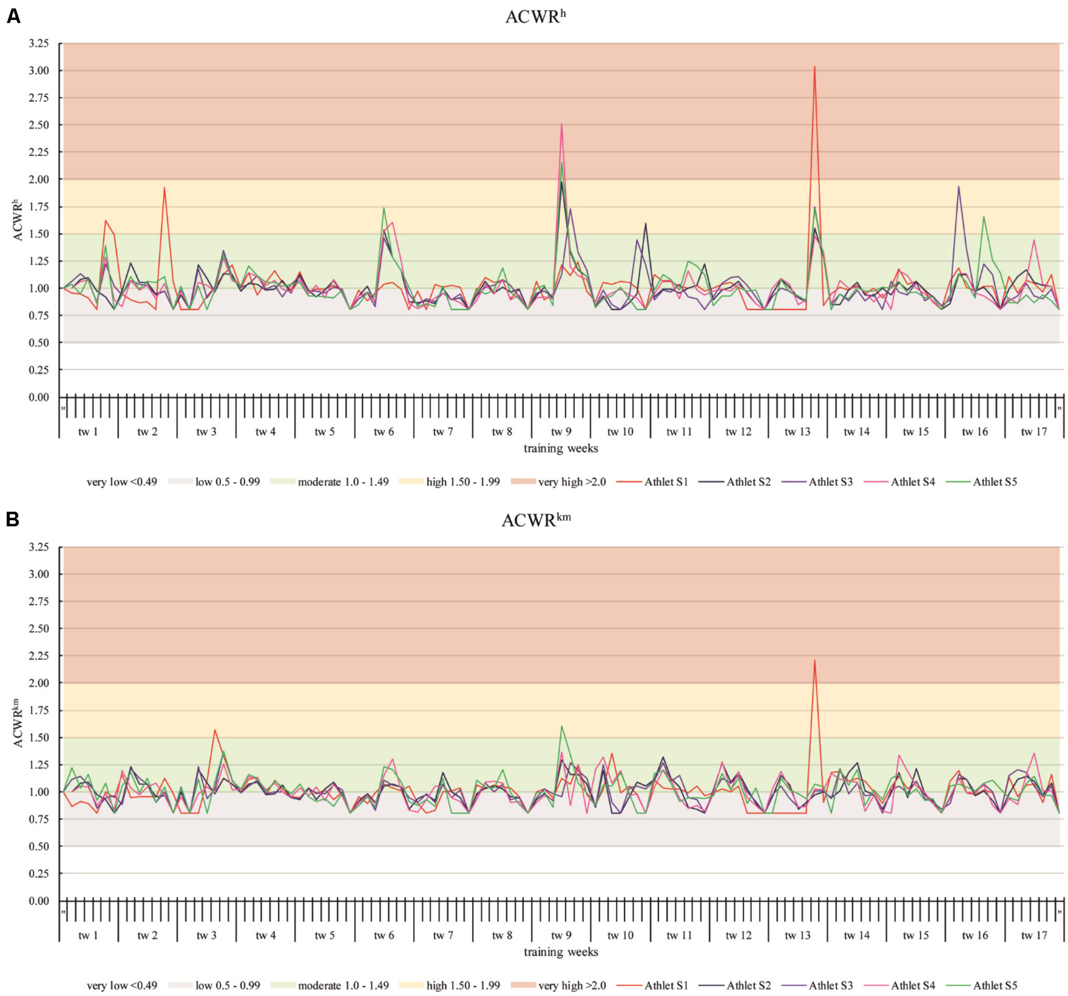

FIGURE 4 | The acute:chronic workload-ratio over 17 training weeks of the athletes S1–S5 based on the $sRPE^{h}$- **(A)** and the $sRPE^{km}$-values **(B)**.

TABLE 2 | Mean (*MCCC*) and range of significant cross-correlations.

		$sRPE^{h}$		$sRPE^{km}$		$ACWR^{h}$		$ACWR^{km}$	
		MCCC	**Range**	***MCCC***	**Range**	***MCCC***	**Range**	***MCCC***	**Range**
Recovery	*PPC*	−0.23	(−0.18/−0.29)	−0.27	(−0.21/−0.35)	−0.27	(−0.27/−0.27)	−0.25	(−0.24/−0.27)
	MPC	−0.20	(−0.18/−0.21)	−0.06	(0.22/−0.32)	−0.18	(−0.18/−0.18)	−0.21	(0.23/−0.24)
	EB	−0.26	(−0.25/−0.28)	0.26	(0.30/−0.24)	−0.25	(−0.22/−0.30)	−0.20	(0.24/−0.20)
	OR	−0.27	(−0.25/−0.30)	**−0.36**	(−0.24/−0.50)	−0.22	(−0.23/−0.41)	−0.27	(−0.18/−0.31)
Stress	*MS*	**0.41**	(0.48/0.33)	**0.52**	(0.66/0.37)	0.22	(0.26/0.18)	0.29	(0.38/0.20)
	LA	0.24	(0.18/0.29)	0.21	(0.29/0.21)	0.23	(0.24/0.22)	0.20	(0.21/−0.21)
	NES	0.24	(0.24/0.24)	0.21	(0.25/−0.26)	0.22	(0.22/−0.19)	0.19	(0.23/−0.25)
	OS	0.29	(0.37/0.24)	**0.39**	(0.46/0.21)	0.26	(0.31/0.22)	0.29	(0.33/0.19)

PPC, Physical Performance Capability, MPC, Mental Performance Capability, EB, Emotional Balance, OR, Overall Recovery, MS, Muscular Stress, LA, Lack of Activation, NES, Negative Emotional State, OS, Overall Stress. MCCC > 0.3 highlighted bold.

approach that takes into account psychological, emotional, cognitive, and social aspects both individually and collectively (Kellmann, 2002b). High inter-individual differences between the athletes lie in strength and direction of the correlation $|0.66| \leq CCC \geq |-0.50|$ as well as in the time delays from lag 0 to lag 7.

Low values in the stress dimensions and high values in the recovery dimensions are generally defined as positive and vice

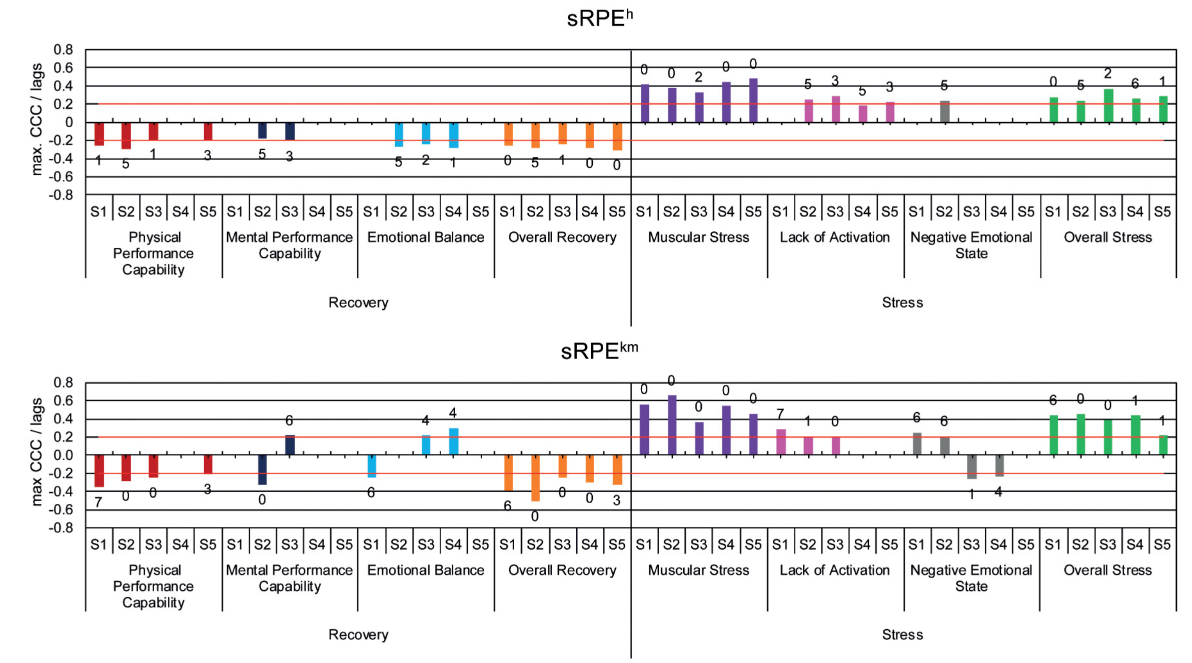

FIGURE 5 | Maximum significant cross correlations (max CCC) between the dimensions of ARSS as lag variables and $sRPE^{h}$ and $sRPE^{km}$ as lead variables with the associated time delay (lags) for the athletes S1 - S5.

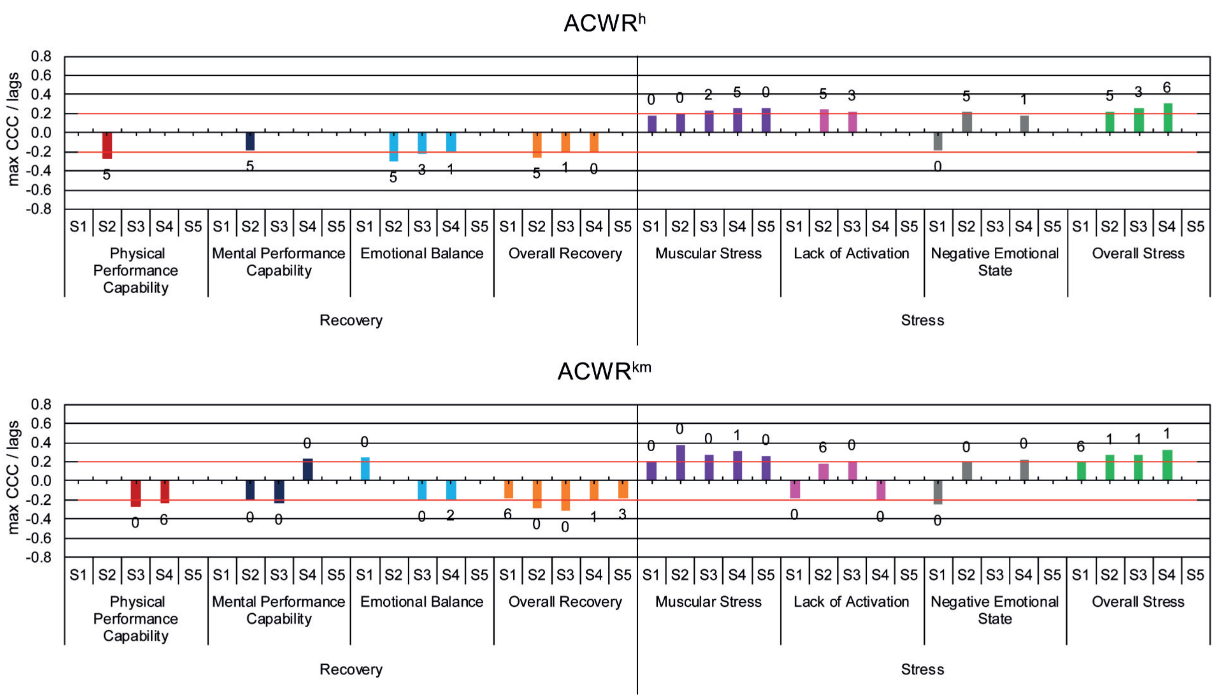

FIGURE 6 | Maximum significant cross correlations (max CCC) between the dimensions of ARSS as lag variables and $ACWR^{h}$ and $ACWR^{km}$ as lead variables with the associated time delay (lags) for the athletes S1–S5.

versa as negative. However, in this context terms like "good – bad" and/or "positive – negative" should be used with care (Kellmann, 2010). The results show that the linear directions of action between the training loads and the individual recovery- and stress-related scales are in contrast to this assumption for three athletes (S1, S3, and S4). High training loads lead to higher

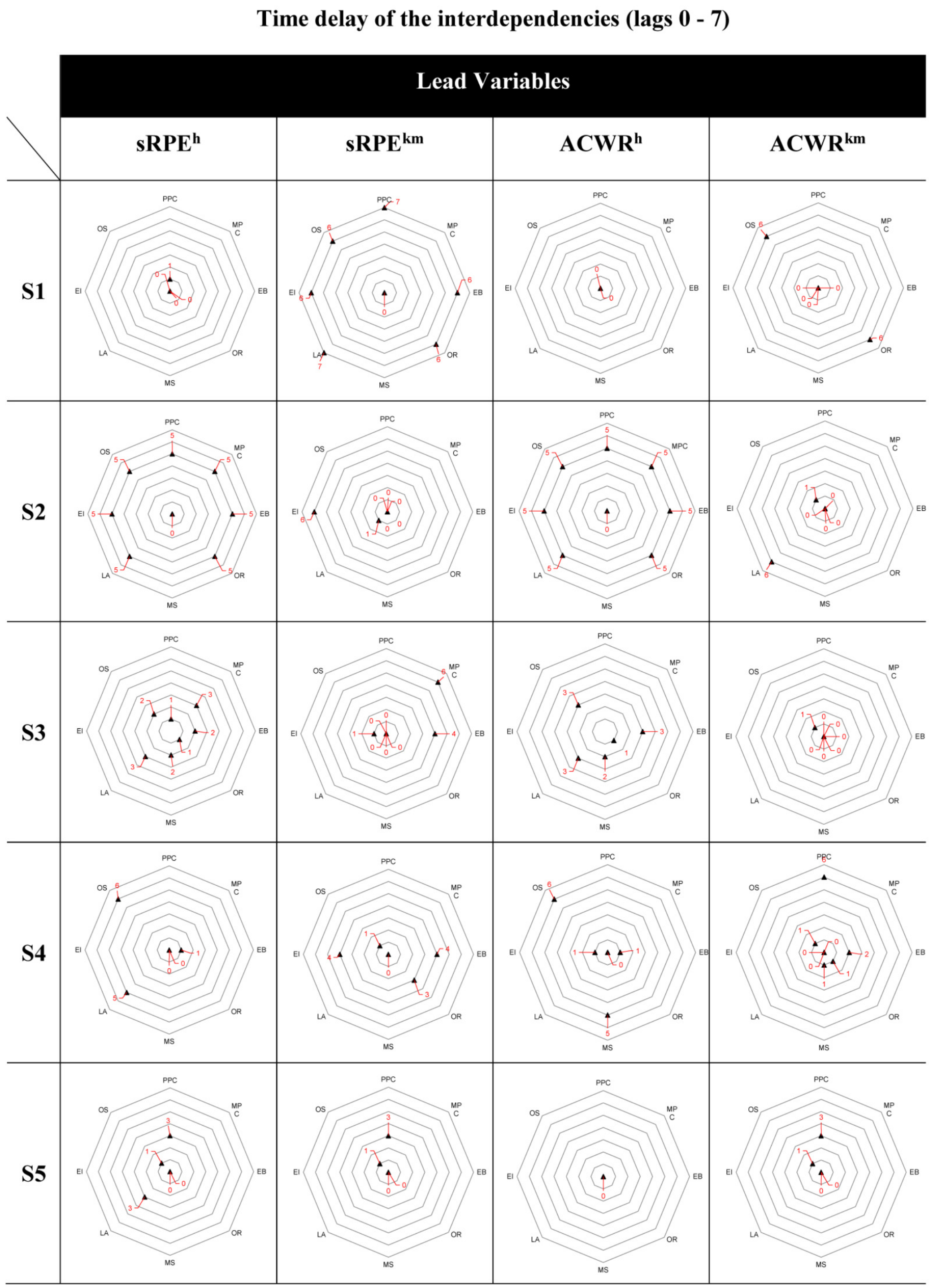

FIGURE 7 | Individual profile display of the time delays (lag 0–7) for the examined athletes S1–S5 for the recovery and stress dimensions of the ARSS with $sRPE^{h}$, $sRPE^{km}$, $ACWR^{h}$, and $ACWR^{km}$ as lead variables on the basis of net diagrams. PPC, Physical Performance Capability; MPC, Mental Performance Capability; EB, Emotional Balance; OR, Overall Recovery; MS, Muscular Stress; LA, Lack of Activation; NES, Negative Emotional State; OS, Overall Stress.

values in the recovery dimensions and lower values in the stress dimensions, however, in different dimensions and with different lead variables. Another aspect is, that the contradictory directions of action exist only for the mental- (*Mental Performance Capacity* and *Lack of Aviation*) and emotional-related scales (*Emotional Balance* and *Negative Emotional State*). In a study of elite rowers Kellmann (2002a) also concluded, that at high training loads, individual recovery parameters, in this case the items *physical* *recovery* and *fun* of the 'Recovery Cue' (Kellmann et al., 2002) can be quite lead to higher values. These results illustrate that the relationship between training load and recovery-stress state cannot be easily generalized, because the interdependencies seem to be too complex and highly individual. A possible explanatory approach can be provided via the 'Individual Zones of Optimal Functioning' model of Hanin (Hanin, 1980, 2002; Salminen et al., 1995; Hanin and Hanina, 2009), which supports the assumption of an individual area or zone in which training loads are more likely to have positive effects on the recovery-stress state. The optimal level of training load does not always occur at the midpoint of the continuum but rather varies from individual to individual. That is, some athletes have a zone of optimal functioning at the lower end of the continuum, some in the midrange, and others in the upper end (Weinberg and Gould, 2007). In addition, the optimal level is most likely not a specific point but rather includes a particular individual range. Another step would be to analyze the relationship of performance against an appropriate modeling to determine individual profiles or individual optimal zones for the dimensions of the ARSS on this basis. In accordance with this, some authors proposed to conduct repeated measurements to establish an individual baseline from which changes can be determined (Saw et al., 2016, 2017; Hecksteden et al., 2017; Hitzschke et al., 2017).

The results support the sensitivity of the ARSS, as the overall and physical-related scales and items showed largest changes in response to the physical stress stimulus. Furthermore, the results underline recent indications from Kölling et al. (2015) and Hitzschke et al. (2017) that the subjective ratings of the physical and overall-related scales *Physical Performance Capacity, Overall Recovery, Muscular Stress* and *Overall Stress* respond on acute load. Nevertheless, mental- and emotional-related scales were affected as well, however, with low cross-correlations. This indicates that these dimensions might be more affected by non-training-induced stressors or factors. For the analysis of the relationship between training load and recovery-stress state the mental- and emotional-related scales seem not to be suitable for this sample.

The difference in time-delay between the sRPE and the ACWR method was expected due to the calculation method of the ACWR using a ratio 1:4 by means of EWMA. The influence of the method for recording the internal load on time delay is clearly visible. Thus, it might be suspected that the ACWR might not be suitable to investigate the time-delayed interdependencies of load and recovery-stress state. However, ACWR still provides a simple and practical method for monitoring load, especially with regards to the control of load intensity over longer periods of time (Hulin et al., 2014; Blanch and Gabbett, 2016; Gabbett et al., 2016; Soligard et al., 2016).

$sRPE^h$ and $sRPE^{km}$ appear to be the more suitable methods for monitoring the interdependencies between load and recovery-stress state, although significant differences were observed. For example, S1 equals profile 1 for $sRPE^h$ and profile 3 for $sRPE^{km}$, whereas the inverse applies to S2 ($sRPE^h$ profile 3 and $sRPE^{km}$ profile 1). Also in terms of the number of CCC and the amount of significant CCC, the sRPE-methods seem to be better suited for monitoring than the ACWR-methods. The results indicate that the more suitable method for swimming is $sRPE^{km}$, which suggests that in swimming the influence of the volume on the perceived exertion is greater than the training time. This has to be further investigated. In particular, because the $sRPE^{km}$ method was used by Nagle et al. (2015) as a modification of Foster's sRPE method (Foster et al., 2001) without previously performing any studies on the comparability of the methods.

Limitations

One limitation of the current study can be seen in the small sample size and that only female athletes were examined. To find a sufficient number of highly trained athletes with high compliance for studies is a general problem. To reach the target position beyond the individual case to a typology or group statements may with this group size only pointing the way for further investigation. From a sports practical point of view, it is clear that single case analysis is sensible and necessary for athlete monitoring. On the other hand, for a scientific generalization based on a group statistic, the sample is too small. So further single case studies are required to investigate whether different types of athletes can be differentiated. Even the decision to perform no 'pre-whitening' for the time series analysis that can lead to 'apparent correlations' in the presence of serial dependence, is to question critically. However, the procedures for how to perform this filtering are particularly controversial for studies with psychological parameters and are in part rejected, especially as there is a risk that the problem will be reversed and 'fake independence' will be present. In addition, it may be criticized that, for the analysis of the relationships between training load and recovery-stress state, the time-delayed effects were examined linear by bivariate cross-correlations and not by multivariate non-linear models. For future investigations, suitable non-linear models should be used or developed. Furthermore, an individual profile or individual optimum recovery-stress zone should be defined, relating to corresponding performance data.

CONCLUSION

Based on our data we conclude that the ARSS, especially the physical and overall-related scales (*PPC, OR, MS, OS*), is a suitable tool for monitoring the acute recovery-stress state in swimmers. Due to its sensitivity to training loads, the individual time-delayed correlations between internal load and recovery-stress state was demonstrated. These interrelationships are considered in relation with CCC > 0.2 to be significant and in many cases as high, e.g., for *Muscular Stress* with $sRPE^{km}$ for athlete S2 (CCC = 0.66).

For *Physical Performance Capability*, *Overall Recovery*, *Muscular Stress* and *Overall Stress* the effectiveness of training load on the recovery-stress state is in line with the theory. *Mental Performance Capability*, *Emotional Balance*, *Lack of Activation,* and *Negative Emotional State* appear to be less training-induced. Comparably high CCC and Ranges result from the four internal load methods, whereby sRPE, especially $sRPE^{km}$, shows a stronger relation to recovery-stress state than ACWR. Based on these results and the individual differences in terms of time delay in training response, we recommend performing intra individual evaluations as well as repeated measurements to establish an individual baseline from which changes can be determined in order to enable a training optimization through individual athletes monitoring. For swimming we also recommend using session RPE, especially sRPE^{km}, to monitor the internal training load and to use the ARSS with focus on physical and overall-scales to monitor the recovery-stress state.

AUTHOR CONTRIBUTIONS

RC planned and designed the study, conducted measurements, analyzed the data, and prepared the manuscript. MP analyzed the data and edited the manuscript. MK, AF, and TM edited the manuscript.

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Effects of Initial Performance, Gross Efficiency and $\dot{V}O_{2peak}$ Characteristics on Subsequent Adaptations to Endurance Training in Competitive Cyclists

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The present study investigated the effects of initial levels of cycling performance, peak oxygen uptake ($\dot{V}O_{2peak}$) and gross efficiency (GE) on the subsequent adaptations of these variables and their relationship following high-intensity training (HIT) designed to increase $\dot{V}O_{2peak}$ in competitive cyclists. Sixty cyclists ($\dot{V}O_{2peak}$ = 61 ± 6 mL kg^{-1} min^{-1}) were assigned a 12-week training program consisting of twenty-four supervised high-intensity interval training sessions and *ad libitum* low intensity training. GE was calculated at 125, 175, and 225 W and performance was determined by mean power during a 40-min time-trial ($Power_{40\,min}$). In addition to correlation analyses between initial level and pre- to post-intervention changes of the different variables, we compared these changes between four groups where participants were categorized with either low and/or high initial levels of $\dot{V}O_{2peak}$ and GE. Average volume of high- and low-intensity training during the 12-week intervention was 1.5 ± 0.3 and 8.3 ± 2.7 h·week^{-1}, respectively. Following the 12-week training period, there was a significant increase in absolute and body mass normalized $\dot{V}O_{2peak}$ and $Power_{40\,min}$ ($p < 0.05$) and a significant decrease in GE ($p < 0.05$) for all athletes pooled. There was no change in body mass following the 12-week training period. We found a moderate negative correlation between initial level of $\dot{V}O_{2peak}$ and the change in $\dot{V}O_{2peak}$ following the training period ($r = -0.32$; $p < 0.05$). A small negative correlation was also found between initial $Power_{40\,min}$ and its change following training both when expressed in absolute power and power normalized for body mass ($r = -0.27$ and -0.28; both $p < 0.05$). A moderate negative correlation was also found between initial levels for GE and its change following training ($r = -0.44$; $p < 0.01$). There were no differences between the four groups based on initial levels of $\dot{V}O_{2peak}$ and GE in the response to training on $\dot{V}O_{2peak}$, GE, or $Power_{40\,min}$ (all $p > 0.12$).

In conclusion, the present findings suggest that there are statistically significant effects of initial levels of cycling performance and $\dot{V}O_{2peak}$ and on the subsequent adaptations following a 12-week HIT program, but the small and moderate effects indicate limited influence on training practice.

Keywords: cycling, performance, maximal oxygen consumption, gross efficiency, high intensity training, interval training

INTRODUCTION

Cycling performance requires high aerobic energy turnover and effective transfer of that energy to external power. Hence, the peak oxygen uptake ($\dot{V}O_{2peak}$) and gross efficiency (GE), defined as the ratio of work rate to metabolic rate, are two key determinants of performance (Joyner and Coyle, 2008). Exercise training interventions focusing on high-intensity training (HIT) in cyclists have repeatedly shown enhanced $\dot{V}O_{2peak}$ as the main physiological adaptation (Lucia et al., 2000; Bacon et al., 2013) whereas GE has been reported to both be unaffected (Ronnestad et al., 2015) and improved (Hintzy et al., 2005; Hopker et al., 2009, 2010). However, the study of Ronnestad et al. (2015), where GE was unaffected, used an effort-based approach to control intensity, which likely induced higher intensity compared to the studies by Hopker et al. (2009, 2010) who regulated intensity by set blood lactate levels. The study by Hintzy et al. (2005) used a combination of moderate- and high-intensity, but the untrained participants in the study are a likely reason for the increased GE. Furthermore, sprint and strength training led to reduced oxygen cost of submaximal cycling (i.e., GE likely increased) (Paton and Hopkins, 2005), whereas low- and moderate-intensity training led to unchanged (Kristoffersen et al., 2014) or increased (Hopker et al., 2012) GE in cycling. Overall, the current literature indicates that both training intensity and fitness level influence the responses on GE.

It is generally believed that greater training loads, achieved through both volume of training and sufficient intensity, are required to trigger $\dot{V}O_{2peak}$ or performance adaptations in individuals with high compared to low initial levels of $\dot{V}O_{2peak}$ or performance. In previous studies, there has been reported an effect of initial level of $\dot{V}O_{2peak}$ on the response to exercise (Saltin et al., 1969), but more recently no significant correlation between initial $\dot{V}O_{2peak}$ and the response to a training intervention was reported (Kohrt et al., 1991; Skinner et al., 2001). However, these studies (Kohrt et al., 1991; Skinner et al., 2001) do not include any measures of performance, and the participants had a relatively low initial level of fitness (reported $\dot{V}O_{2peak}$ < 31.8 mL kg^{-1} min^{-1}). As such, inference to performance and/or more highly trained populations cannot be made based on these studies.

The interaction between $\dot{V}O_{2peak}$ and GE adaptations in response to a training intervention requires further elucidation. An inverse relationship between $\dot{V}O_{2peak}$ and GE has been found (Lucia et al., 2002) and also an inverse relationship between the change in GE and $\dot{V}O_{2peak}$ following a training intervention (Santalla et al., 2009; Hopker et al., 2012). However, none of these interventions led to increased $\dot{V}O_{2peak}$ at the group level.

Therefore, the purpose of the present study was to investigate how baseline characteristics of cycling performance, $\dot{V}O_{2peak}$ and GE influence subsequent adaptations of these parameters and their interplay following a 12-week high-intensity intervention designed to increase $\dot{V}O_{2peak}$ in competitive cyclists. We hypothesized that a large training load would lead to increased $\dot{V}O_{2peak}$ and reduced GE, but there would be no influence of initial levels of $\dot{V}O_{2peak}$ and GE.

MATERIALS AND METHODS

Sixty-three male competitive cyclists (38 ± 8 year, $\dot{V}O_{2peak}$: 61 ± 6 mL kg^{-1} min^{-1}) were recruited to take part in the current multicentre study, involving three test centers completing the same experimental trial. All participants were categorized as well-trained (Jeukendrup et al., 2000) with 9 ± 3 h of weekly training in the year prior to participation. All participants completed the intervention, however, three participants were excluded from the final analyses due to absence from post-testing. The study was approved by the ethics committee of the Faculty for Health and Sport Science, University of Agder, and registered with the Norwegian Social Science Data Services (NSD). All athletes gave their verbal and written informed consent prior to study participation. The present study is part of a larger research project and thus, the intervention period, testing procedures and instrument are described in brief. A detailed description of the intervention period, testing procedures, and instruments can be found in Sylta et al. (2016).

Intervention Period

In brief, after a 6-week preparation and familiarization period, the training intervention consisted of three 4-week mesocycles. During the last week in each mesocycle, participants were advised to reduce low-intensity training (LIT) volume by 50% compared to previous weeks. In addition, HIT session frequency was reduced from 3 to 1 during the last week of each mesocycle. In total, each participant was prescribed twenty-four supervised HIT sessions in addition to testing and self-organized *ad libitum* LIT. All training was recorded using an online training diary and a heart rate monitor was worn for all exercise training. Three different HIT session models were utilized and all included a self-selected warm up of 20–30 min of LIT, followed by four high intensity interval efforts of 4, 8, or 16 min at a self-selected cadence, separated by 2 min rest, followed by 10–20 min of LIT as a cool-down. All HIT training was performed while supervised on Computrainer cycling trainers (RacerMate Inc., Seattle, WA, United States) using the participants' own bikes and, additionally, blood lactate measurements were taken from a selection of the participants on each session. The participants were instructed to cycle at their maximal sustainable intensity for the entire session, and provided with continuous feedback regarding cadence, heart rate (HR), and power output. All participants were prescribed the same number of the three different HIT session models.

Testing Procedures

In brief, on test *day 1,* a submaximal, incremental exercise test consisting of 5-min steps was performed on a bicycle ergometer at work rates of 125, 175, and 225 W. $\dot{V}O_2$ and the respiratory exchange ratio (RER) was used to calculate the metabolic rate during the three work rates. The work rate was then divided by the metabolic rate to calculate GE. The 125, 175, and 225 W work rates used to calculate GE corresponded to 34 ± 4, 48 ± 5, and 61 ± 6% of the participants' peak power output (PPO) and to 43 ± 4, 53 ± 5, and 65 ± 6% of their $\dot{V}O_{2peak}$ achieved during the incremental test. $\dot{V}O_2$, RER, and HR were measured during the last 2.5 min of each step when a steady state condition had occurred. Blood lactate was measured after 4.5 min of each step. After 10 min recovery, an incremental test to exhaustion was performed starting with 1 min of cycling at 3 W kg^{-1} (rounded down to nearest 50 W) and subsequent increases of 25 W every minute. Strong verbal encouragement was provided throughout the test. $\dot{V}O_{2peak}$ was calculated as the average of the two highest consecutive 30-s $\dot{V}O_2$ measurements and PPO was calculated as the mean power output during the final 60 s the participants were able to maintain power output during the incremental test. HR_{peak} was observed during the final 5 s before exhaustion and blood lactate was measured 60 s post-exhaustion.

On test day 2, participants performed a 40-min time trial ($Power_{40min}$) after a 30-min warm-up at a self-selected power output. The $Power_{40min}$ test was conducted under supervision in a well-ventilated room. The temperature and relative humidity were similar at the pre- and post-tests and on both occasions *ad libitum* water intake was allowed. Participants were blinded to all feedback except for elapsed time and the participants were instructed to cycle at the highest possible mean power output for 40 min.

Instruments and Materials

In brief, all physiological tests were performed on a cycling ergometer [Velotron (RacerMate, Seattle, WA, United States) or Lode Excalibur Sport (Lode B. V., Groningen, Netherlands)] adjusted to the participant's preference. The type of ergometer was consistent at pre- and post-tests. Participants were instructed to remain seated during all tests, with self-selected cadence. Performance tests and all HIT sessions were performed using each participant's personal road bike mounted on Computrainer Lab™ trainers (RacerMate, Seattle, WA, United States), calibrated according to the manufacturer's specifications. $\dot{V}O_2$ was measured using Oxycon Pro™ with mixing chamber (Oxycon, Jaeger GmbH, Hoechberg, Germany) calibrated using gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger) was calibrated using a 3L calibration syringe (5530 series; Hans Rudolph, Kansas, MO, United States). HR was measured using Polar V800 (Polar Electro Oy, Kempele, Finland) and blood lactate was measured using capillary blood samples taken from the fingertip (Biosen C-Sport, EKF diagnostics, Cardiff, United Kingdom).

Data Analysis

Four subgroups (each with $N = 8$) were identified from the complete cohort, characterized by high or low $\dot{V}O_{2peak}$ relative to body mass and high or low GE. $\dot{V}O_{2peak}$ and GE rank within the cohort from the pre-test was used as criteria for selecting participants to the respective groups (**Figure 1**). The HH (high GE and high $\dot{V}O_{2peak}$) and LL (low GE and low $\dot{V}O_{2peak}$) groups were selected to yield the highest and lowest average rank for $\dot{V}O_{2peak}$ and GE, respectively. The HL (high GE and low $\dot{V}O_{2peak}$) group was selected to have the highest $\dot{V}O_{2peak}$ rank while maintaining an average rank as close to the mean as possible and LH (low GE and high $\dot{V}O_{2peak}$) group was selected to have the highest possible GE score while maintaining an average rank as close to the mean as possible.

Statistical Analyses

Pearsons correlation coefficients were calculated to determine relationships between cycling performance, $\dot{V}O_{2peak}$ and GE and a descriptors of effect sizes of the correlations were calculated according to http://www.sportsci.org/resource/stats/effectmag.html. Differences between PRE and POST conditions were evaluated using a one-way ANOVA. Differences in responses among the four different groups were evaluated using a two-way repeated measures ANOVA. We calculated the smallest worthwhile change in performance as 0.20 multiplied with the standard deviation (SD) at the pre-test (Hopkins et al., 2009). All data analyses were conducted using SPSS 22.0 (SPSS Inc, Chicago,

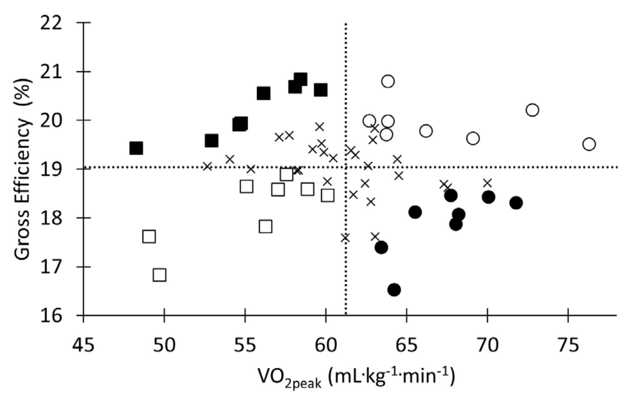

FIGURE 1 | Participant distribution of $\dot{V}O_{2peak}$ relative to body mass and GE at the baseline measurement. Open circles indicate participants in the HH (high $\dot{V}O_{2peak}$ and high efficiency) group. Filled circles indicate participants in the HL (high $\dot{V}O_{2peak}$ and low efficiency) group. Filled squares indicate participants in the LH (low $\dot{V}O_{2peak}$ and high efficiency) group. Open squares indicate participants in the LL (low $\dot{V}O_{2peak}$ and low efficiency) group. X indicates subjects not included in any of the sub groups ($N = 28$). Dotted lines indicate the mean value for $\dot{V}O_{2peak}$ and gross efficiency.

IL, United States) and are presented as mean ± SD with statistical significance accepted as $\alpha \leq 0.05$.

RESULTS

$\dot{V}O_{2peak}$ ranged from 48 to 76 mL·kg^{-1} min^{-1} and GE from 16.5 to 20.8%. The average Power$_{40min}$ ranged from 194 to 342 W and 2.3 to 4.6 W kg^{-1} when expressed as absolute values and normalized to body mass, respectively. A plateau in $\dot{V}O_2$ occurred in 54 and 58 out of the 60 pre- and post-tests, respectively. Following the 12-week training intervention, there was a significant increase in $\dot{V}O_{2peak}$, PPO, and Power$_{40min}$ but there was a decrease in GE (**Table 1**; all $p < 0.05$). The weekly training volume during the intervention was 10 ± 3 h, of which 97 ± 4% was endurance training. The mean power output during all HIT intervals was 310 ± 40 W and average blood lactate taken during the sessions was 8.7 ± 4.0 mmol L^{-1}. The overall intensity distribution for all training based on heart rate data is presented in **Figure 2**.

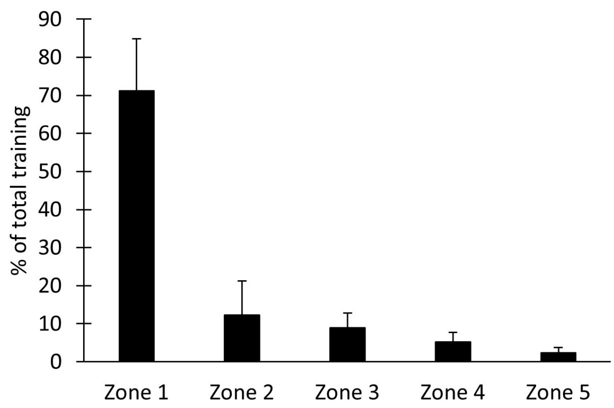

FIGURE 2 | Intensity distribution from heart rate monitored training throughout the study. Zone 1: <75% of HR$_{peak}$, zone 2: 75–85% HR$_{peak}$, zone 3: 85–90% of HR$_{peak}$, zone 4: 90–95% of HR$_{peak}$, and zone 5: >95% of HR$_{peak}$.

Initial Characteristics

Initial absolute $\dot{V}O_{2peak}$ did not correlate significantly with the change in $\dot{V}O_{2peak}$ (**Figure 3A**) following the 12-week intervention (**Figure 2A**; $r = -0.18$; $p = 0.17$). However, for $\dot{V}O_{2peak}$ expressed relative to body mass, there was a moderate significant negative correlation between the initial values and the change in $\dot{V}O_{2peak}$ following the intervention (**Figure 3B**; $r = -0.32$; $p < 0.05$). Smallest worthwhile changes for body mass normalized $\dot{V}O_{2peak}$, GE, and body mass normalized performance during the Power$_{40min}$ were 1.2 mL kg^{-1} min^{-1}, 0.18%, and 0.08 W kg^{-1}, respectively.

There was a significant negative moderate correlation between initial GE and percentage change in GE following the 12-week intervention (**Figure 4**; $r = -0.44$; $p < 0.01$). There was no change in cadence during the stages used for GE calculation from the pre- to the post-test ($p = 0.35$).

TABLE 1 | Pre- and post-test values of performance and physiological factors following the 12-week high-intensity training intervention in 60 well-trained cyclists.

	Pre	Post
$\dot{V}O_{2peak}$ (mL min^{-1})	4859 ± 462	5078 ± 484*
$\dot{V}O_{2peak}$ (mL kg^{-1} min^{-1})	61 ± 6	65 ± 6*
GE (%)	19.0 ± 0.9	18.6 ± 0.9*
PPO (W)	372 ± 40	384 ± 29*
PPO (W kg^{-1})	4.7 ± 0.5	4.9 ± 0.4*
Power$_{40min}$ (W)	282 ± 30	301 ± 31*
Power$_{40min}$ (W kg^{-1})	3.6 ± 0.4	3.9 ± 0.4*
Peak blood lactate (mmol L^{-1})	12.1 ± 2.3	12.7 ± 2.1
RER	1.15 ± 0.1	1.15 ± 0.1
Body mass (kg)	80 ± 8	78 ± 8

Peak oxygen uptake ($\dot{V}O_{2peak}$), gross efficiency (GE) averaged from 125, 175, and 225 W, peak power output from the incremental test (PPO), average power output during the 40-min time trial (Power$_{40min}$), peak blood lactate, and RER-values from the incremental test and body mass are presented as arithmetic mean (±SD). Asterisks indicate a significant change from the pre- to post-test ($p < 0.05$).

Initial performance during the Power$_{40min}$ displayed a small negative correlation with the change in performance following the training intervention both when expressed as absolute values (**Figure 5A**; $r = -0.28$; $p < 0.05$) and relative to body mass (**Figure 5B**; $r = -0.27$; $p < 0.05$). Initial PPO showed small and moderate correlations with the change following the intervention both for absolute power output ($r = -0.23$; $p = 0.08$) and values relative to body mass ($r = -0.42$; $p < 0.01$), respectively.

GE and $\dot{V}O_{2peak}$ Relationship and Their Relationship With Performance

There was a moderate negative correlation between GE and both absolute $\dot{V}O_{2peak}$ (**Figure 6A**; $r = -0.36$, $p < 0.01$) and $\dot{V}O_{2peak}$ relative to body mass (**Figure 6B**; $r = -0.27$, $p < 0.05$).

There were significant moderate correlations between change in performance during the Power$_{40min}$ and change in absolute $\dot{V}O_{2peak}$ ($r = 0.30$, $p < 0.05$) and $\dot{V}O_{2peak}$ relative to body mass (**Figure 7A**; $r = 0.38$, $p < 0.01$). There was no significant correlation between change in performance during the Power$_{40min}$ and change in GE (**Figure 7B**; $r = -0.06$, $p = 0.63$).

Sub-group Analyses

Characteristics of the participants included in the four sub-groups are presented in **Table 2**. The HH group showed the best performance on both the incremental and the time-trial test, but only when the results where normalized for body mass. Total training volume, LIT, and HIT did not differ between the four subgroups (all $p > 0.36$).

There was a significant main effect of the training intervention on $\dot{V}O_{2peak}$, Power$_{40min}$ (**Figure 8**; all $p < 0.05$) and PPO (not shown) during the incremental test. However, there was no difference between the four groups in the change in $\dot{V}O_{2peak}$, PPO, Power$_{40min}$ or GE (all $p > 0.12$) and all four groups maintained the selection characteristics following the intervention (i.e., the HH and HL had higher $\dot{V}O_{2peak}$ compared to the LH and LL and the HH and LH had higher GE compared to the HL and LL) (all $p < 0.05$).

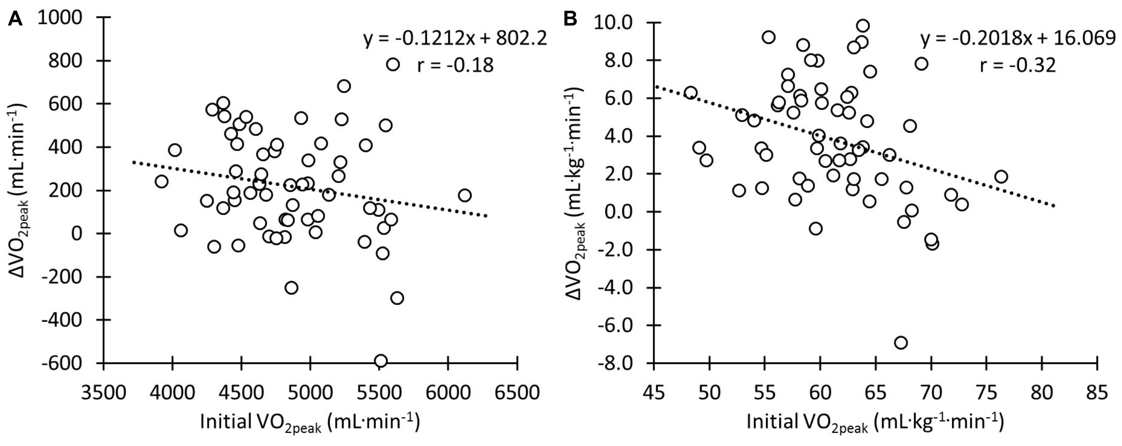

FIGURE 3 | Correlation between the change in $\dot{V}O_{2peak}$ during the training intervention and initial $\dot{V}O_{2peak}$ in absolute values **(A)** and normalized for body mass **(B)**.

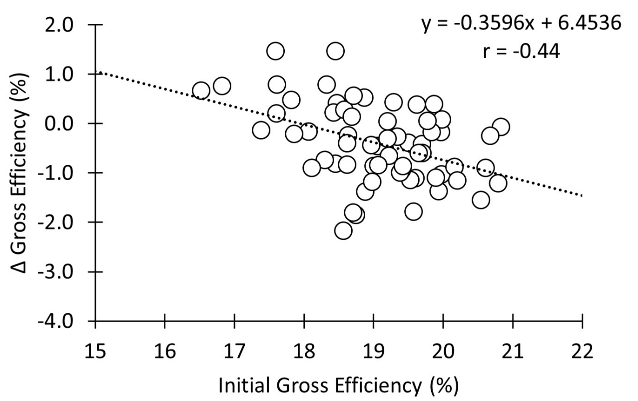

FIGURE 4 | Correlation between the percentage change in gross efficiency during the training intervention and initial gross efficiency.

DISCUSSION

The purpose of the present study was to investigate how the initial characteristics of cycling performance, $\dot{V}O_{2peak}$, and GE, as well as their interplay, influences subsequent adaptations in these parameters following a 12-week HIT intervention in well-trained cyclists.

The training intervention led to an increase in performance and $\dot{V}O_{2peak}$ but a decrease in GE. Furthermore, we found significant associations between the athletes' initial levels of GE, $\dot{V}O_{2peak}$, and performance and subsequent adaptations of that same parameter. However, parameter specific initial levels explained only 4–18% of the variance in adaptations, and when we compared our four groups with combinations of high and/or low initial levels of GE and $\dot{V}O_{2peak}$, no differences in adaptations were found among groups. Overall, our study shows that the impact of initial characteristics of cycling performance, $\dot{V}O_{2peak}$, and GE on the subsequent responses to these parameters are relatively small, and the effect disappears if we investigate the relationship in groups based on initial GE and $\dot{V}O_{2peak}$ characteristics in combination.

While the present study shows significant effects of initial performance and $\dot{V}O_{2peak}$ on the subsequent adaptation to HIT in highly trained cyclists, the effect is only moderate. An effect of initial fitness on the $\dot{V}O_{2peak}$ responses has also been reported previously in less trained individuals (Saltin et al., 1969), although other studies (Kohrt et al., 1991; Skinner et al., 2001) showed no effect. The HIT element in the present study had an overall positive effect on $\dot{V}O_{2peak}$ and endurance performance, which differs from the previous studies that utilized a lower training intensity (e.g., 75% of $\dot{V}O_{2peak}$ (Skinner et al., 2001)). Furthermore, the total training load added in our study seemed to be sufficient to elicit an overload stimulus and thereby trigger endurance adaptions in most of the athletes. This is exemplified by a recent study where further increasing the training load effectively elicited training adaptations in participants who were unresponsive to 180 min of moderate to high intensity exercise per week (Montero and Lundby, 2017). However, even in our study, the observed improvements were relatively modest, which may partly be due to differences in how optimal the added training load was for each individual participant. In addition, the subsequent recovery phase is of importance for adaptations, and e.g., subjects need to be healthy and avoid other factors which might negatively influence adaptations.

In contrast to the positive effects of the 12-week high intensity training intervention on $\dot{V}O_{2peak}$ (∼5%), GE declined slightly following the intervention (∼2%), and there was a moderate association between initial level of GE and the subsequent response. However, there were no significant differences in adaptation between the groups with high and low GE. Previous literature examining changes in GE following high intensity training reported no effect (Ronnestad et al., 2015) or an increase in GE when utilizing an exercise intensity equivalent to five heart rate beats above the work rate eliciting 4 $mmol{\cdot}L^{-1}$ of blood lactate (Hopker et al., 2010). However, previous studies in participants of a similar performance level to our participants, who utilized low- to moderate-intensity training,

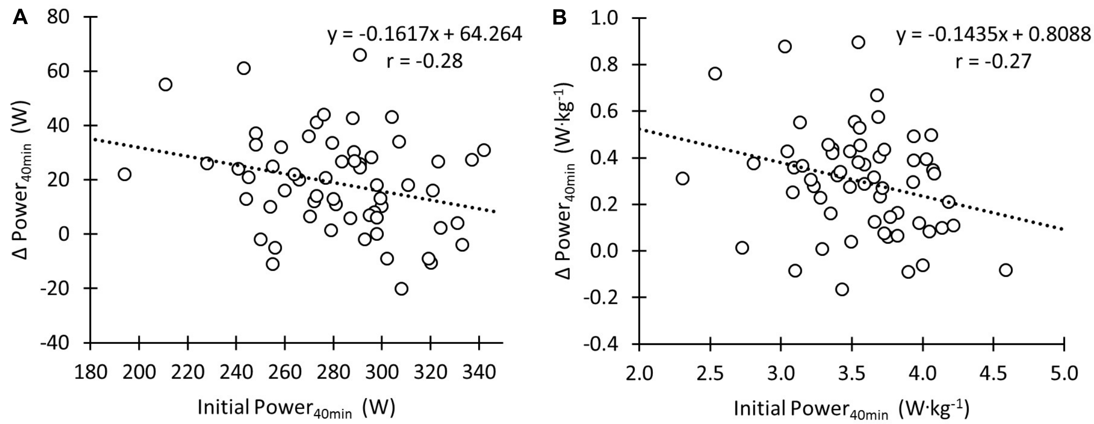

FIGURE 5 | Correlation between the change in time trial performance during the training intervention and initial time trial performance (Power$_{40min}$) in absolute units **(A)** and normalized for body mass **(B)**.

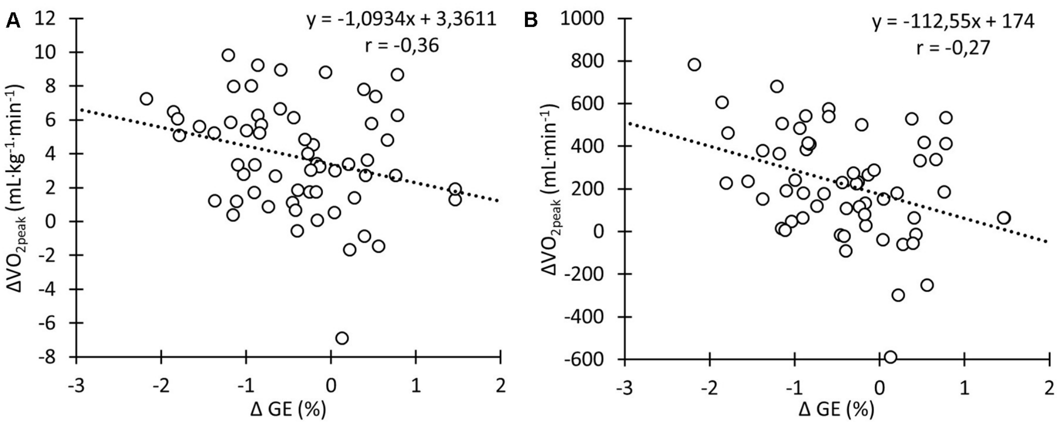

FIGURE 6 | Correlation between changes in $\dot{V}O_{2peak}$ relative to body mass **(A)** and absolute $\dot{V}O_{2peak}$ **(B)** and changes in gross efficiency (GE) during the training intervention.

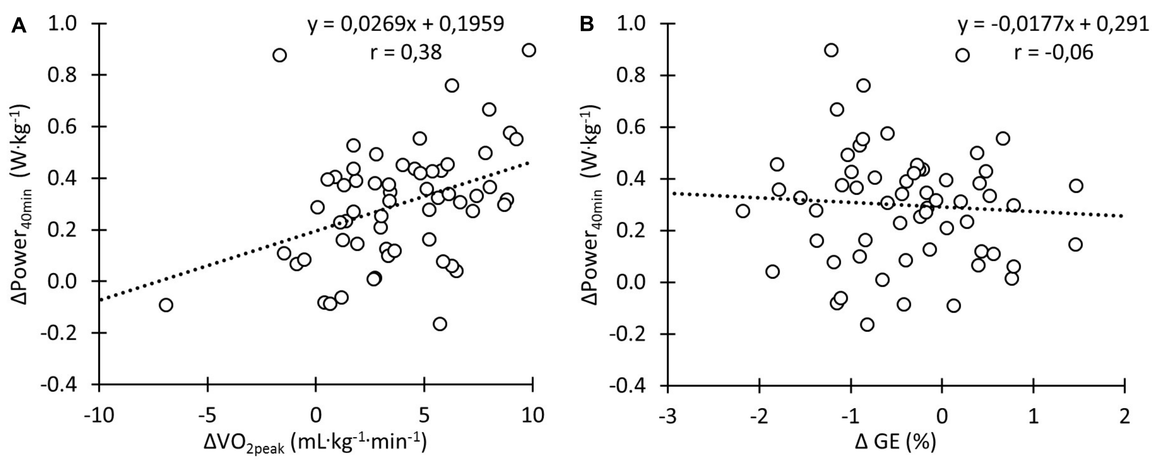

FIGURE 7 | Correlation between change in 40-min time trial performance normalized for body mass and change in $\dot{V}O_{2peak}$ normalized for body mass **(A)** and between changes in 40-min time trial performance normalized for body mass and changes in gross efficiency **(B)** during the training intervention.

TABLE 2 | Pre-test characteristics and training data during the 12-week intervention period for the four sub-groups.

	Hi $\dot{V}O_{2peak}$/Hi GE	Hi $\dot{V}O_{2peak}$/Low GE	Low $\dot{V}O_{2peak}$/Hi GE	Low $\dot{V}O_{2peak}$/Low GE
Age (years)	32 ± 6^{cd}	36 ± 6^{d}	41 ± 6^{a}	44 ± 4^{ab}
Height (cm)	181 ± 9	184 ± 5	181 ± 4	184 ± 6
Heart rate peak (bpm)	194 ± 7	194 ± 10	184 ± 9	185 ± 13
Body mass (kg)	71.3 ± 7.9^{bcd}	79.6 ± 2.7^{ad}	80.9 ± 3.2^{ad}	88.9 ± 10.3^{abc}
$\dot{V}O_{2peak}$ (mL min^{-1})	4784 ± 509^{b}	5362 ± 268^{acd}	4622 ± 460^{b}	4916 ± 488^{b}
$\dot{V}O_{2peak}$ (mL kg^{-1} min^{-1})	67.3 ± 5.0^{cd}	67.4 ± 2.8^{cd}	57.2 ± 3.4^{ab}	55.5 ± 4.1^{ab}
GE (%)	19.9 ± 0.4^{bd}	17.9 ± 0.7^{ac}	20.1 ± 0.7^{bd}	18.2 ± 0.7^{ac}
PPO (W)	367 ± 43	394 ± 38	367 ± 43	361 ± 46
PPO (W kg^{-1})	5.2 ± 0.4^{cd}	4.9 ± 0.4^{cd}	4.5 ± 0.5^{abd}	4.1 ± 0.4^{abc}
Power$_{40min}$ (W)	283 ± 22	282 ± 20	274 ± 40	281 ± 39
Power$_{40min}$ (W kg^{-1})	4.0 ± 0.3^{abc}	3.5 ± 0.2^{a}	3.4 ± 0.5^{a}	3.2 ± 0.5^{a}
HIT volume (h week^{-1})	1.4 ± 0.3	1.5 ± 0.3	1.5 ± 0.3	1.6 ± 0.7
LIT volume (h week^{-1})	9.1 ± 3.7	7.3 ± 2.0	7.3 ± 2.4	7.7 ± 2.3

Pre-test values for the HH (high $\dot{V}O_{2peak}$ and high efficiency), HL (high $\dot{V}O_{2peak}$ and low efficiency), LH (low $\dot{V}O_{2peak}$ and high efficiency), and LL (low $\dot{V}O_{2peak}$ and low efficiency) groups. $\dot{V}O_{2peak}$, gross efficiency (GE), peak power output from the incremental test (PPO) and average power output during the 40-min time trial (Power$_{40min}$) are presented as mean (±SD). [a]Indicates a difference from HH ($p < 0.05$). [b]Indicates a difference from HL ($p < 0.05$). [c]Indicates a difference from LH ($p < 0.05$). [d]Indicates a difference from LL ($p < 0.05$).

reported improved GE and a significant positive relationship between changes in GE and performance (Hopker et al., 2010, 2012).

A potential explanation for the different effect of training on GE between our study and others might be the HIT applied in our study, which primarily influenced performance via enhanced $\dot{V}O_{2peak}$ (Sylta et al., 2016)). Previous studies (Hopker et al., 2010, 2012) have used a lower intensity compared to the present study, and a lower intensity may be more effective for enhancing GE at a submaximal work rate. In the present study, training was executed as HIT with the addition of *ad libitum* LIT. A possible influencing factor on the decline in GE in the present study may be the low amount of training as moderate-intensity exercise, which may be important for maintaining GE (Hopker et al., 2009; Kristoffersen et al., 2014).

Intensity in the present study was controlled utilizing an effort based approach where the participants are instructed to aim to achieve the highest possible average power output within each session (Seiler et al., 2013). This is the same approach used by Ronnestad et al. (2015) who demonstrated unchanged GE after HIT training. It is possible that the effort based intensity control leads to higher intensity, as shown through the high blood lactate levels during intervals in the present (i.e., average blood lactate of 8.9 mmol L^{-1}) and a previous study using intervals of 4 to 8 min duration (Seiler et al., 2013), compared to the approaches used by Hopker et al. (2010) who demonstrated increased GE with intensity based on absolute blood lactate levels of 4 mmol L^{-1} + 5 heart rate beats per minute. Furthermore, Hopker et al. (2009, 2010) proposed that training at moderate intensity, eliciting less than 4 mmol L^{-1} blood lactate, is important for maintaining GE. Hence, training at (very) high-intensity may lead to unchanged or declined GE, whereas training at lower intensity may have the opposite effect.

However, the decline in GE may also be influenced by the fact that it was calculated at a moderate intensity (i.e., the average of 125, 175, and 225 W) and might not reflect what occurs at higher workloads (i.e., training intensity average interval work rate of 310 W). Additionally, since 225 W exceed 60% of PPO, there is a possibility that the $\dot{V}O_2$ slow component influence our measurements slightly, which could have led to an overestimation of the decline in GE from pre- to post-test. However, since there was no difference in the change in GE for the three work rates used for GE calculation and the corresponding RER measurements were below 1.0, a possible influence would be minor.

As expected, we found a positive relationship between change in cycling performance and change in $\dot{V}O_{2peak}$. In contrast, change in GE was not related to a change in performance. This inverse relationship between the change in GE and $\dot{V}O_{2peak}$ (**Figure 5**) corresponds with previous findings (Lucia et al., 2002; Hopker et al., 2012). However, in contrast to previous studies which have shown an increase in GE and small changes in $\dot{V}O_{2peak}$ (Lucia et al., 2002; Hopker et al., 2012), we show the same inverse relationship when the average GE decreases and the average $\dot{V}O_{2peak}$ increases.

Also contrary to previous findings (Hopker et al., 2012) is an increased performance despite a decrease in GE. Although the 12-week HIT intervention led to a large increase in $\dot{V}O_{2peak}$ that positively influenced cycling performance, it appears that cycling efficiency is slightly reduced, especially in those with large $\dot{V}O_{2peak}$ improvements. However, it is important to keep in mind the relatively short duration of the intervention executed in this study. As demonstrated by the findings in this study, the decrease in GE over a relatively short period where the objective of training is to increase $\dot{V}O_{2peak}$ was not detrimental to performance due to the improved $\dot{V}O_{2peak}$. However, in general, long-term decreases in GE can be detrimental to performance. Since studies using low- and moderate-intensity training, as well as sprint and strength training (Paton and Hopkins, 2005; Hopker et al., 2012) have shown increases in GE, cyclists should likely use a combination of different training intensities to optimize their long-term performance development. This also

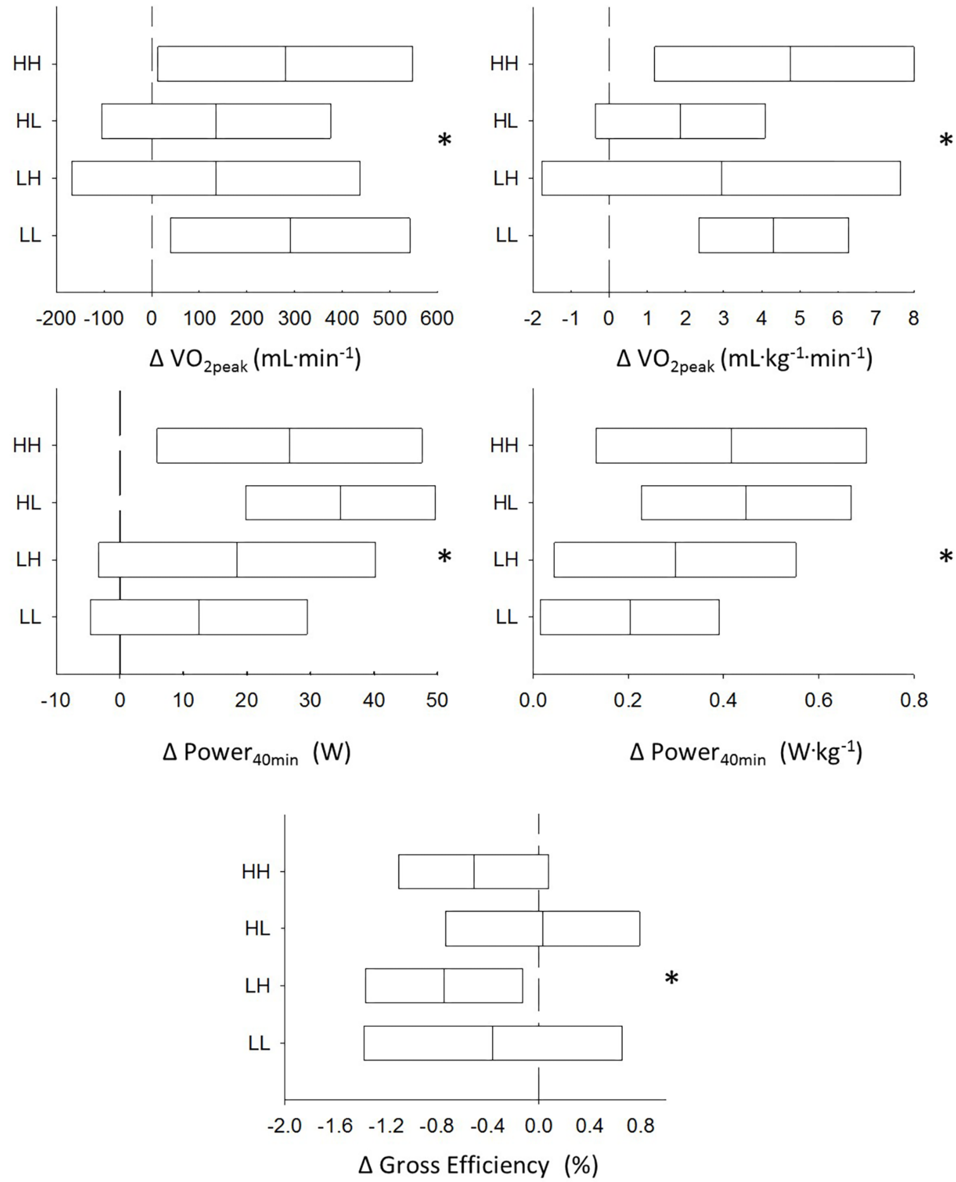

FIGURE 8 | Group responses from the pre-test to the post-test for the HH (high $\dot{V}O_{2peak}$ and high efficiency), HL (high $\dot{V}O_{2peak}$ and low efficiency), LH (low $\dot{V}O_{2peak}$ and high efficiency), and the LL (low $\dot{V}O_{2peak}$ and low efficiency) groups for $\dot{V}O_{2peak}$, time trial performance and gross efficiency (GE). *Indicates a significant main effect of the training intervention.

represents a typical training pattern over a season for elite cyclists, where a combination of intensities and periods with different focus is employed (Lucia et al., 2000; Hopker et al., 2009). Although different types of training influence GE and $\dot{V}O_{2peak}$ differently, both high and moderate intensity training may be necessary for optimal performance increases during a competitive season. Additionally, the long-term effect on GE and $\dot{V}O_{2peak}$ is potentially different from the effects seen in this relatively short 12-week intervention compared to the effect on performance.

We believe the finding of a small effect of baseline level has important practical implications and demonstrates that if an appropriate training stimulus is administered, the initial physiological characteristics have little effect on the training adaptation in a large cohort of well-trained athletes. It demonstrates that an appropriate training stimulus can further enhance performance, independent of the initial physiological characteristics of even well-trained athletes. A known limitation of the present arises from the baseline characteristic and change following the intervention are not independent measurements, we violate the assumption of independence in the correlation analyses. This may lead to an effect known as regression to the mean (Altman and Bland, 1994) which ultimately would lead to an overestimation of the correlation. When calculated using

Oldham's correction to minimize the effect, the correlations in the present study were weakened. The additional finding that the groups based on differences in baseline characteristics show no difference in the adaptation to the training intervention also supports our interpretation. Although the groups in the present study where comprised of only eight athletes which limit statistical power with multiple comparisons, however, the group size is comparable to similar studies on training adaptation.

CONCLUSION

In conclusion, the present study demonstrates statistically significant, but practically trivial effects of initial levels of $\dot{V}O_{2peak}$ and performance on subsequent adaptations following a 12-week HIT intervention in well-trained cyclists. In contrast to the improvements in performance and $\dot{V}O_{2peak}$ following this intervention, GE was reduced and the changes in GE negatively correlated with changes in $\dot{V}O_{2peak}$. However, when comparing adaptations between groups with different levels of $\dot{V}O_{2peak}$ and/or GE, we found no differences. Overall, this study indicates that the effects of initial level of performance and physiological capacities on subsequent adaptations are relatively small, and the effect disappears if we investigate the relationship in groups based on GE and $\dot{V}O_{2peak}$ characteristics.

AUTHOR CONTRIBUTIONS

KS, ØSa, ET, JD, BR, and ØSy contributed in conceptualization the study. KS, ØSa, DH, and JD contributed in data collection. KS, ØSa, DH, and ØSy contributed in data handling and statistical analysis. KS, ØSa, ET, DH, JD, SS, BR, and ØSy contributed in preparing the manuscript.

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Adaptive Changes After 2 Weeks of 10-s Sprint Interval Training With Various Recovery Times

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Purpose: The aim of this study was to compare the effect of applying two different rest recovery times in a 10-s sprint interval training session on aerobic and anaerobic capacities as well as skeletal muscle enzyme activities.

Methods: Fourteen physically active but not highly trained male subjects (mean maximal oxygen uptake 50.5 ± 1.0 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$) participated in the study. The training protocol involved a series of 10-s sprints separated by either 1-min (SIT10:1) or 4-min (SIT10:4) of recovery. The number of sprints progressed from four to six over six sessions separated by 1–2 days rest. Pre and post intervention anthropometric measurements, assessment of aerobic, anaerobic capacity and muscle biopsy were performed. In the muscle samples maximal activities of citrate synthase (CS), 3-hydroxyacylCoA dehydrogenase (HADH), carnitine palmitoyl-transferase (CPT), malate dehydrogenase (MDH), and its mitochondrial form (mMDH), as well as lactate dehydrogenase (LDH) were determined. Analysis of variance was performed to determine changes between conditions.

Results: Maximal oxygen uptake improved significantly in both training groups, by 13.6% in SIT10:1 and 11.9% in SIT10:4, with no difference between groups. Wingate anaerobic test results indicated main effect of time for total work, peak power output and mean power output, which increased significantly and similarly in both groups. Significant differences between training groups were observed for end power output, which increased by 10.8% in SIT10:1, but remained unchanged in SIT10:4. Both training protocols induced similar increase in CS activity (main effect of time $p < 0.05$), but no other enzymes.

Conclusion: Sprint interval training protocols induce metabolic adaptation over a short period of time, and the reduced recovery between bouts may attenuate fatigue during maximal exercise.

Keywords: Wingate anaerobic test, all-out exercise, skeletal muscle, enzyme activity, recovery

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INTRODUCTION

The study by Parolin et al. (1999) described metabolic modifications in skeletal muscle during three 30-s bouts of maximal isokinetic cycling separated by 4-min recovery periods. This exercise protocol has become a basis for sprint interval training (SIT). The studies investigating the effect of SIT have been conducted using three to seven 30-s supramaximal exercise sprint bouts with 4-min rest periods between (Vollaard et al., 2017). Since the aerobic contribution in ATP resynthesis increases in consecutive exercise bouts (Bogdanis et al., 1996; Parolin et al., 1999), SIT is associated with the elevation of muscular oxidative potential as well as central adaptations such as increased cardiac output and stroke volume (Sloth et al., 2013). Consequently, SIT is postulated as a time-efficient exercise strategy for improving maximal oxygen uptake (VO_2max) (Sloth et al., 2013; Vollaard et al., 2017) with biochemical and morphological adaptations arising in as little as six sessions performed over 2 weeks (Burgomaster et al., 2005, 2006, 2008; Hazell et al., 2010; Lloyd Jones et al., 2017).

It has been suggested that some of the adaptations to SIT are associated with the power generated during the first few seconds of each sprint. Therefore, shorter exercise bouts have been investigated to determine whether resulting adaptations are similar to those observed following 30-s SIT (Hazell et al., 2010; Lloyd Jones et al., 2017). Two various SIT protocols consisting of repeated 30-s or 10-s "all-out" cycle sprints with 4-min rest intervals, performed over 2 weeks indicate comparable enhancement in aerobic and anaerobic exercise capacities (Hazell et al., 2010). Moreover, similar improvements in performance are observed after applying SIT protocols matched for total sprint time −4 × 30-s or 20 × 6-s (Lloyd Jones et al., 2017). Another key factor affecting the metabolic modulations may be the work to rest ratio. Reduction in recovery time seems to be less effective in evoking adaptive changes (Hazell et al., 2010). The increase in aerobic and anaerobic capacities following 10-s SIT with 4-min rest are double changes in 10-s SIT with 2-min rest (Hazell et al., 2010).

Therefore, the aim of the present study was to compare the effect of applying two different rest intervals in 10-s SIT. We hypothesized that reducing the recovery time to 1-min in the SIT protocol consisting of repeated 10-s "all-out" cycle sprints, performed over 2 weeks would be less effective in evoking aerobic adaptations than 10-s SIT with 4-min rest, however it would still improve anaerobic performance measures.

Abbreviations: SIT, sprint interval training; VO_2max, maximal oxygen uptake; VE, minute ventilation; HR, heart rate; MAP, maximal aerobic power; AT, anaerobic threshold; TW, total work; PPO, peak power output; MPO, mean power output; EPO, end power output; FI, fatigue index; FFM, fat free mass; SMM, skeletal muscle mass; BMI, body mass index; CS, citrate synthase; HADH, 3-hydroxyacylCoA dehydrogenase; CPT, carnitine palmitoyl-transferase; MDH, malate dehydrogenase; mMDH, mitochondrial malate dehydrogenase; cMDH, cytoplasmic malate dehydrogenase; LDH, lactate dehydrogenase; EDTA, ethylenediaminetetraacetic acid; DTNB, 5,5′-dithiobis (2-nitrobenzoic acid); OAA, oxaloacetic acid; NADH, nicotinamide adenine dinucleotide reduced form.

MATERIALS AND METHODS

Fourteen physically active but not highly trained male subjects at mean VO_2max 50.5 ± 1.0 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ volunteered to participate in the study. The subjects were asked to refrain from any additional exercise practice during the study. The study was approved and then completed in accordance with the recommendations of Local Bioethics Committee (http://www.komisjabioetyczna.pl). Written informed consent was obtained from all subjects. The study was conducted in accordance with the Declaration of Helsinki. The overall study protocol is shown in **Figure 1**. The subjects were assigned to either 1-min interval recovery (SIT10:1) or 4-min interval recovery (SIT10:4) based on the pre-training results.

Anthropometric Measurements

Body mass and composition were estimated using InBody720 (InBody Co., Ltd., Seoul, Korea). Participants were asked to arrive at the laboratory fasted, with voided bladders and bowels. The bioelectrical impedance analyses were performed in the position recommended by the manufacturer guidelines and the subjects clad only in briefs (Ziemann et al., 2013). The impedance measured five segments of the body (arms, trunk, legs) at frequencies of 1, 5, 50, 250, 500, and 1,000 kHz through the eight electrodes. Based on these impedance values fat free mass (FFM) and skeletal muscle mass (SMM) were calculated.

Cardiopulmonary Exercise Test

To determine VO_2max participants performed a graded cycle ergometry test on an electromagnetically-braked, cycle ergometer (ER 900 Jaeger, Viasys Healthcare GmbH, Germany). After a 5-min warm-up at the intensity of 1.5 $W \cdot kg^{-1}$ with a pedaling cadence of 60 rpm, work rate was increased by 25 $W \cdot min^{-1}$ until volitional exhaustion. Breath by breath pulmonary gas exchange was measured by Oxycon-Pro analyzer (Viasys Healthcare GmbH, Germany; Olek et al., 2012). Heart rates were monitored continuously by telemetry (S-625, Polar Electro-Oy, Finland). Maximal heart rate (HRmax), maximal ventilation (VEmax), maximal aerobic power (MAP) were calculated at the VO_2max level (Ziemann et al., 2011). The anaerobic threshold (AT) has been determined by three independent members of the research group using nonlinear increase in ventilation.

Anaerobic Power Measurement

After the standard warm-up, all subjects performed a 30-s "all-out" supramaximal test on a mechanically braked cycle ergometer (884E Sprint Bike, Monark, Sweden). The test was initiated from a dead stop with the resistance equal to 75 g·kg body $mass^{-1}$ (corresponding to 7.5% of an individual's body mass) preset on the ergometer's friction belt (Laskowski et al., 2011). The obtained results were analyzed for total work (TW), peak power output (PPO), mean power output (MPO), end power output (EPO), time to PPO (Bar-Or, 1987). Fatigue index (FI) was determined by taking the percentage difference between PPO and EPO (Richardson et al., 2016).

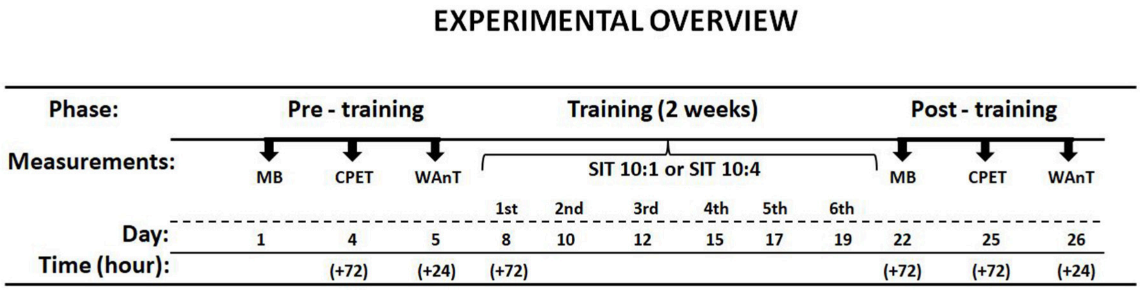

FIGURE 1 | Scheme of the study protocol. Muscle biopsy (MB), cardiopulmonary exercise test (CPET), Wingate anaerobic test (WAnT).

Muscle Sampling and Analyses

Muscle biopsy was made under local anesthesia (2% lidocaine), in the supine position. The sample was obtained by the sterile single-use micro biopsy needle (M.D.L. srl, Delebio, Italy). The section of the *Vastus Lateralis* muscle (∼10 mg) was immediately frozen in liquid nitrogen and stored in −80°C until analysis. All biopsies were collected by the same person to ensure a standard localization and muscle depth.

Muscles were homogenized in an ice-cold buffer contained 50 mM potassium phosphate, 1 mM ethylenediaminetetraacetic acid (EDTA), 1 mM threo-1,4-dimercapto-2,3-butanediol at pH 7.4. The homogenates were then centrifuged at 600 g at 4 °C for 10 min. The obtained supernatant was used to determine enzyme activities as previously (Antosiewicz et al., 1995; Kaczor et al., 2005; Olek et al., 2013) with a Super Aquarius CE9200 spectrophotometer (Cecil Instruments Ltd., Cambridge, UK) at 30°C. Citrate synthase (CS) activity was measured by the rate of SH production as CoASH using the thiol reagent 5,5′-dithiobis (2-nitrobenzoic acid) (DTNB). The reagent cocktail contained 50 mM potassium phosphate, 0.1 mM DTNB, and 0.1 mM acetylCoA. The reaction was started by 0.1 mM oxaloacetic acid (OAA). Carnitine palmitoyl-transferase (CPT) activity was measured in the reaction mixture composed by 60 mM of Tris HCl at pH 8.0, 1.5 mM of EDTA with 0.05% Triton X-100 and 0.25 mM DTNB and 1.67 mM of carnitine. The reaction was started by the addition of 0.025 mM palmitoyl-CoA. The kinetics of change in absorbance were followed at 412 nm, and the molar absorption coefficient 14,150 $M^{-1}cm^{-1}$ was used for calculation of CS and CPT activities. 3-hydroxyacylCoA dehydrogenase (HADH) activity was determined in a buffer containing 100 mM potassium phosphate and 0.05% Triton at pH 7.4. After addition of supernatant and 0.1 mM NADH the cuvette was preincubated for 3 min. The reaction was started by 0.1 mM acetoacetyl-CoA. Malate dehydrogenase (MDH) activity was determined in the 50 mM Tris-HCl buffer pH 7.6 containing 5 mM EDTA, 0.1 mM NADH, and 0.2 mM OAA. For the mitochondrial MDH (mMDH) assay, the cytoplasmic form of the enzyme (cMDH) was inactivated by 3 min preincubation of homogenate with equal volume of ethanol 99.5% (v/v) at room temperature. Then mMDH activity was followed by the same procedure as for total MDH measurements. Lactate dehydrogenase (LDH) activity was measured in the assay medium contained 50 mM potassium phosphate, 1 mM EDTA, 0.1 mM NADH, 2.1 mM pyruvate, at pH 7.2. The substrates NADH and pyruvate were added immediately before the measurement was started. The change in absorbance was followed in time at 340 nm. HADH, MDH, and LDH activities were calculated using molar absorption coefficient of NADH 6,220 M^{-1} cm^{-1}. Protein content was determined by using Bradford protein assay. All reagents were obtained from Sigma-Aldrich.

Training Intervention

Subjects participated in training sessions on Monday, Wednesday, and Friday for 2 weeks. The same research assistant supervised all sessions, controlled the flywheel resistance, as well as the time of exercise and recovery periods. Each training session began with a 5-min warm-up at the intensity approximating 30% MAP. All training was completed using a load of 75 g·kg body $mass^{-1}$.

1. SIT10:1; performed repeated, 10-s "all-out" efforts separated by 1-min recovery.
2. SIT10:4; performed repeated, 10-s "all-out" efforts separated by 4-min recovery.

The number of repeats increased from four repetitions during the first two training sessions, by five repetitions during the middle two training sessions, to six repetitions for the final two training sessions as has been done previously (Hazell et al., 2010). Both training groups performed a similar training protocol consisting of: 30-min low intensity warm-up and 5-min high intensity exercise throughout the training intervention (Stöggl and Sperlich, 2015). The difference between the groups was the time of recovery between the 10-s exercises. Therefore, overall time of training sessions was equal 59-min for SIT10:1 and 131-min for SIT10:4 (**Table 1**).

Statistical Analyses

Two-way analysis of variance ANOVA was performed to examine the main effects of group and/or time. In case the ANOVA yielded a significant effect, a Tukey's HSD test was used for *post hoc* comparisons. A probability level $p < 0.05$ was considered statistically significant. Due to the small number of subjects, the effect size (η^2) has been calculated. The values of η^2 has been interpreted as follows: 0.1 a small effect, 0.3 a medium effect and 0.5 a large effect, as previously (Olek et al., 2014). All data are expressed as mean ± SEM (standard error of mean).

TABLE 1 | Training distribution over the 2-weeks intervention.

	SIT10:1	SIT10:4
Total time (min)	59	131
Low intensity (% of total time)	50.8	22.9
High intensity (% of total time)	8.5	3.8
Recovery (% of total time)	40.7	73.3

The intensity of exercise and its distribution over time have been classified as previously described (Stöggl and Sperlich, 2015).

TABLE 2 | Anthropometric characteristics of participants.

	SIT10:1	SIT10:4
Age (years)	20.1 ± 0.3	20.7 ± 0.2
Height (cm)	180 ± 1	185 ± 2
Body mass (kg)	75.9 ± 1.7	83.1 ± 2.7[#]
FFM (kg)	66.4 ± 1.5	73.6 ± 2.6[#]
SMM (kg)	37.8 ± 0.9	42.3 ± 1.5[#]
BMI	23.5 ± 0.5	24.3 ± 0.5

Values are means ± SEM. FFM, fat free mass; SMM, skeletal muscle mass; BMI, body mass index. [#]$p < 0.05$ as compared to SIT10:1.

RESULTS

The mean body mass of SIT10:4 subjects was higher than SIT10:1 subjects (**Table 2**), therefore physiological parameters have been presented as relative values. There were no significant differences between groups in aerobic and anaerobic capacities as well as skeletal muscle enzymatic activities at baseline.

The training elevated VO_2max in both groups (**Table 3**), by 13.6% in SIT10:1 and 11.9% in SIT10:4 ($p < 0.001$, $\eta^2 = 0.63$), with no difference between the groups. Moreover, there was a significant VEmax increase ($p < 0.05$, $\eta^2 = 0.29$) after the training. No significant differences in either HRmax or MAP were observed.

Significant changes in oxygen uptake ($p < 0.001$, $\eta^2 = 0.78$), VE ($p < 0.001$, $\eta^2 = 0.74$) and workloads (%MAP) ($p < 0.001$, $\eta^2 = 0.72$) at the exercise intensity corresponding to AT intensity following 2 weeks of SIT were observed (**Table 3**). No significant main effects for group and group × time interaction in these parameters were noted.

Wingate anaerobic test results indicated main effect of time for TW ($p < 0.001$, $\eta^2 = 0.79$; **Figure 2A**), MPO ($p < 0.001$, $\eta^2 = 0.79$; **Figure 2B**) and PPO ($p < 0.001$, $\eta^2 = 0.67$; **Figure 2D**) which increased significantly in both groups. However, these changes did not differ between the groups. Significant differences between training groups ($p < 0.05$, $\eta^2 = 0.32$), time ($p < 0.01$, $\eta^2 = 0.48$) and a group x time interaction ($p < 0.02$, $\eta^2 = 0.39$) were recorded for EPO (**Figure 2C**). EPO in SIT10:1 increased significantly by 10.8% ($p < 0.005$), whereas in SIT10:4 group remained unchanged ($p = 0.9$). Changes in EPO affected FI, which approached statistical significance after the training ($p = 0.07$, $\eta^2 = 0.25$; **Figure 2E**). No differences in time to PPO was noted (**Figure 2F**).

There was a main effect of time for CS activity, which elevated significantly in both training groups ($p < 0.05$, $\eta^2 = 0.33$), but no for HADH ($p = 0.18$, $\eta^2 = 0.14$), mMDH ($p = 0.17$, $\eta^2 = 0.15$) and CPT ($p = 0.9$, $\eta^2 = 0.0$). There were no differences in LDH activity and LDH/CS ratio (**Table 4**).

DISCUSSION

The main finding of this study is that both 1-min and 4-min recovery intervals in repeated 10-s sprint intervention for 2 weeks, resulted in a similar improvements in aerobic (VO_2max, AT) and anaerobic (TW, PPO, MPO) capacities, and skeletal muscle enzyme activities. Moreover, the shorter recovery time induced higher EPO and lower FI during Wingate anaerobic test.

TABLE 3 | Aerobic capacities before (pre) and after (post) 2 weeks of SIT.

	SIT10:1		SIT10:4	
	Pre	**Post**	**Pre**	**Post**
MAX				
VO_2 ($mlO_2 \cdot min^{-1} \cdot kg^{-1}$)[a]	51.4 ± 1.4	58.4 ± 2.2	49.6 ± 1.5	55.5 ± 2.1
VE ($L \cdot min^{-1}$)[c]	143 ± 6	159 ± 8	152 ± 7	155 ± 6
MAP ($W \cdot kg^{-1}$)	3.9 ± 0.2	4.0 ± 0.2	3.8 ± 0.1	3.9 ± 0.1
HR (bpm)	194 ± 4	191 ± 4	192 ± 1	192 ± 2
AT				
VO_2 ($mlO_2 \cdot min^{-1} \cdot kg^{-1}$)[a]	34.0 ± 1.4	39.2 ± 1.2	34.2 ± 1.5	38.2 ± 1.6
VE ($L \cdot min^{-1}$)[a]	67 ± 3	80 ± 3	71 ± 4	77 ± 3
Power ($W \cdot kg^{-1}$)[b]	2.5 ± 0.1	2.7 ± 0.1	2.3 ± 0.1	2.7 ± 0.2
Power (% MAP)[a]	63 ± 3	67 ± 3	62 ± 2	69 ± 2
HR (bpm)	164 ± 4	163 ± 5	154 ± 3	161 ± 4

Values are means ± SEM. VO_2, oxygen uptake; VE, minute ventilation; MAP, maximal aerobic power; HR, heart rate. [a]$p < 0.001$ main training effect; [b]$p < 0.005$ main training effect; [c]$p < 0.05$ main training effect.

The increase in VO_2max is similar to data obtained by McGarr et al. (2014) and Richardson and Gibson (2015), who used 30-s sprints with 4-min recoveries in training protocols performed over 2 weeks, reporting 14.2 and 11.2% improvement, respectively. Hazell et al. (2010), by applying six SIT sessions consisting of 10-s sprints with 4-min recovery intervals, indicated an 8.5% enhancement in aerobic capacity, similar to 30-s "all-out" cycles interspersed with 4-min recoveries (8.3%) reported in the same study. However, the workload used during SIT was slightly higher (10% of individual's body mass) (Hazell et al., 2010) than in the current protocol (7.5% of individual's body mass). On the contrary, two other studies applying 10-s maximal cycling SIT reported no change in VO_2max: 2.4% (Hellsten-Westing et al., 1993) and −1.3% (Skleryk et al., 2013). These discrepancies may be caused by the number of repetitions applied during SIT (Vollaard et al., 2017). SIT performed by Hellsten-Westing et al. (1993) consisted of 15 10-s maximal sprints, three times per week for a total of 6

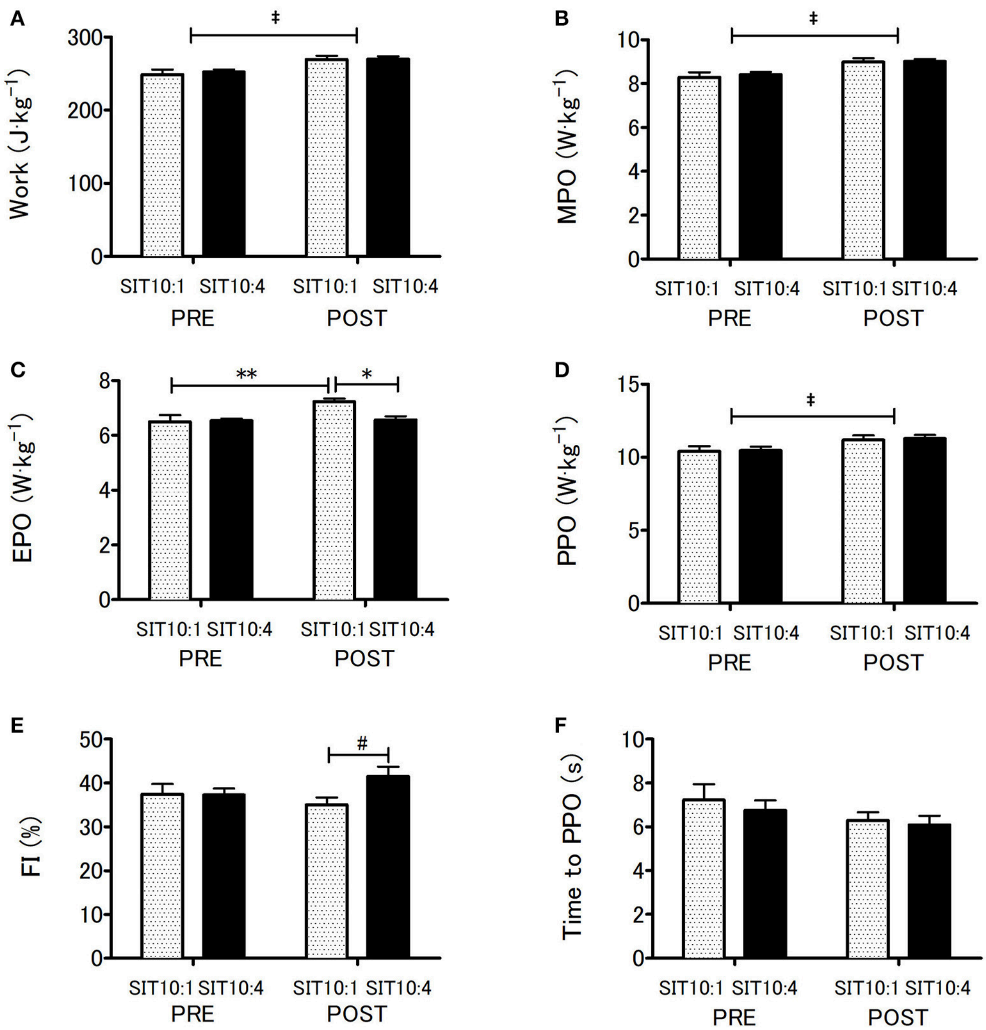

FIGURE 2 | Anaerobic capacity before and after 2 weeks of SIT. Total work **(A)**, mean power output **(B)**, end power output **(C)**, peak power output **(D)**, fatigue index **(E)** and time to peak power output **(F)**. $^{‡}p < 0.001$ main training effect; $^{*}p < 0.01$ as compared to post-training between the groups; $^{**}p < 0.005$ as compared to pre-training within the group; $^{\#}p = 0.07$ main effect of group.

weeks. Skleryk et al. (2013) implemented six SIT sessions of 10-s "all-out" cycling, repeated 8–12 times. In the recent meta-analysis, Vollaard et al. (2017) indicated that training protocols consisting of fewer repetitions during session induced greater VO_2max increase. Authors negated the role of total energy use, energy turnover or oxygen transfer in improvement of VO_2max with SIT, because for each of these factors the stimulus should be greater with more sprint repetitions (Vollaard et al., 2017).

Our results revealed that 1-min or 4-min rest periods did not impact the increase in relative values of VO_2max. Both training protocols were characterized by supramaximal intensity. Despite being short-lasting, both had a positive effect on maximal ventilation values, allowing subjects to perform the high volume workload. Moreover, maximal oxygen uptake also strongly correlates with skeletal muscle mitochondrial capacities (Rasmussen et al., 2001). SIT-induced VO_2max improvement is associated with changes in mitochondrial bioenergetics (Larsen et al., 2013). Six SIT sessions of 30-s sprints, performed over 2 weeks caused maximal CS activity elevation (Burgomaster et al., 2005, 2006). On the other hand, HADH, the rate-limiting fat oxidation mitochondrial enzyme, does not change after 2 weeks (Burgomaster et al., 2006), however, it significantly increases after 6 weeks of 30-s SIT (Burgomaster et al., 2008). Higher HADH has also been observed in legs, but not in arms, following 72 "all-out sprints" (36 with arm cycling and 36 with leg cycling separated by 1-h of recovery) during the seven training sessions (Zinner et al., 2016). We have shown that a SIT protocol consisting the same number of repetitions as previously reported (Burgomaster et al., 2005, 2006), although with lower total work done, induced a significant rise in CS activity (but not in other mitochondrial enzymes).

TABLE 4 | Maximal activities of skeletal muscle enzymes before (pre) and after (post) 2 weeks of SIT.

	SIT10:1		SIT10:4	
	Pre	**Post**	**Pre**	**Post**
CPT (mU·mg protein^{-1})	1.6 ± 0.1	1.6 ± 0.1	1.7 ± 0.1	1.7 ± 0.1
CS (mU·mg protein^{-1})[a]	161 ± 19	193 ± 13	177 ± 13	202 ± 13
HADH (mU·mg protein^{-1})	116 ± 11	132 ± 5	114 ± 11	123 ± 12
MDH (U·mg protein^{-1})	5.2 ± 0.7	5.4 ± 0.5	4.9 ± 0.5	5.9 ± 0.6
cMDH (U·mg protein^{-1})	3.9 ± 0.5	4.0 ± 0.3	3.7 ± 0.4	4.4 ± 0.4
mMDH (U·mg protein^{-1})	1.3 ± 0.2	1.4 ± 0.1	1.2 ± 0.1	1.5 ± 0.2
LDH (U·mg protein^{-1})	3.2 ± 0.4	3.8 ± 0.2	3.6 ± 0.5	3.8 ± 0.3
LDH/CS	20.3 ± 0.8	20.2 ± 2.1	20.8 ± 2.5	19.6 ± 2.6

Values are means ± SEM. CPT, carnitine palmitoyl-transferase; CS, citrate synthase; HADH, 3-hydroxyacylCoA dehydrogenase; MDH, malate dehydrogenase; cMDH, cytoplasmic malate dehydrogenase; mMDH, mitochondrial malate dehydrogenase; LDH, lactate dehydrogenase. [a]$p < 0.05$ main training effect.

Since training induced changes in muscle CS activity are matched by changes in whole body oxidative capacity (Vigelsø et al., 2014; Meinild Lundby et al., 2018), our results confirm the effectiveness of both SIT protocols in training-induced adaptations.

Elevated oxidative ATP synthesis, attenuates the contribution of anaerobic ATP production (Larsen et al., 2014) and delays the blood lactate accumulation (Jakeman et al., 2012) following SIT. We have not determined lactate production, but we have observed changes in maximal oxygen uptake and CS activity, which were associated with higher workload at the intensity corresponding to AT. In addition, aerobic/anaerobic energy supply depends on the rate of pyruvate production and its mitochondrial oxidative decarboxylation catalyzed by pyruvate dehydrogenase competing to cytosolic reduction to lactate via LDH (Spriet et al., 2000). Moreover, malate-aspartate shuttle appears to be quantitatively important in lactate production during exercise (Schantz et al., 1986). Although the training protocol applied in our study did not modify LDH activity, and the increase in MDH activity was not statistically significant, we have observed higher workout at the intensity corresponding to AT, suggesting reduced lactate production following SIT.

SIT performed daily for 2 weeks increases skeletal muscle phosphocreatine (PCr) content and creatine kinase (CK) activity, but not PPO nor MPO during the Wingate test (Parra et al., 2000; Rodas et al., 2000). On the contrary, the same 14 sessions applied for 6 weeks (resting for 2 days between each session) causes improvement in PPO and MPO with no change in PCr and CK (Parra et al., 2000). PPO increases with no modification in PCr also after completing only 6 SIT sessions over 2 weeks (Burgomaster et al., 2005). Similarly, higher PPO has been reported in a study utilizing 6 sessions of 10-s supramaximal bouts, with 2-min or 4-min recoveries between sprints (Hazell et al., 2010). Consistently, we observed a significant PPO increase in both SITs. Despite no differences between the two protocols in other measured parameters, we observed an improvement in EPO during Wingate test in the group with a shorter recovery time.

Aerobic energy provision contributes almost half of the ATP turnover during the repeated 30-s sprint (after 4-min recovery; Bogdanis et al., 1996). Hence, the adaptive changes in oxidative metabolism seem to be reasonable following such a training protocol. During the 10-s sprint, the PCr availability is important for high power output (Bogdanis et al., 1998). Since PCr resynthesis 2-min after cessation of exercise reaches about ∼90% of the resting value (Hultman et al., 1967; Bogdanis et al., 1998), subjects are able to reproduce PPO after 2-min recovery (Bogdanis et al., 1998). It seems that the reported adaptations following such training protocols may be caused by increased flux in the creatine-PCr energy shuttle (Bessman and Carpenter, 1985). Bessman and Savabi (1988) suggested that creatine plays important role in high energy phosphate transport, necessary for protein synthesis, ion transport and muscle contraction. The PCr resynthesis 1-min and 4-min after the exercise is ∼80 and 90% (Hultman et al., 1967), consequently the small difference seems to be insufficient to induce various adaptive response for two SIT protocols. On the other hand, accumulation of incomplete recoveries in 1-min recovery SIT may contribute to some adaptations in ionic regulation resulting in EPO improvement. However, an increasing number of sprints may accumulate fatigue (Vollaard et al., 2017) and thus the effectiveness of training protocol in aerobic adaptations may be reduced (Hellsten-Westing et al., 1993; Skleryk et al., 2013).

CONCLUSION

This study found that 2 weeks of SIT comprising either of 1- or 4-min recovery time between exercises, which were matched for total sprint time, elicited similar performance changes in fit, healthy men. Moreover, reduced time of recovery between bouts may be more effective in attenuating fatigue during maximal exercise. Overall, obtained data complement presently available knowledge about interactions between intensity as well as duration of interval protocols and recovery. This is particularly significant in the context of the latest recommendations of American College of Sports Medicine; which cites high/sprint intensity interval training as the most effective form of exercise (Thompson, 2017).

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of Local Bioethics Committee with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

The protocol (**Figure 1**) was approved by the Local Bioethics Committee (http://www.komisjabioetyczna.pl/).

AUTHOR CONTRIBUTIONS

RO, SK, and RL: Conceived and design the experiment; RO, SK, EZ, WZ, and RL: Performed the data collection; RO and PW: Performed the statistical analysis and interpretation of data; RO, SK, EZ, WZ, PW, and RL: Participated in drafting the article or revising it critically for important intellectual content; RO, SK, EZ,WZ, PW, and RL: Approved the final manuscript.

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Impact of Short-Term Training Camp on Aortic Blood Pressure in Collegiate Endurance Runners

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To investigate the influence of short-term vigorous endurance training on aortic blood pressure (BP), pulse wave analysis was performed in 36 highly trained elite collegiate endurance runners before and after a 7-day intense training camp. Subjects participated three training sessions per day, which mainly consisted of long distance running and sprint training to reach the daily target distance of 26 km. After the camp, they were divided into two groups based on whether the target training was achieved. Aortic systolic BP, pulse pressure, and tension-time index (TTI, a surrogate index of the myocardial oxygen demand) were significantly elevated after the camp in the accomplished group but not in the unaccomplished group, whereas the brachial BP remained unchanged in both groups. The average daily training distance was significantly correlated with the changes in aortic systolic BP ($r = 0.608$, $p = 0.0002$), pulse pressure ($r = 0.415$, $p = 0.016$), and TTI ($r = 0.438$, $p = 0.011$). These results suggest that aortic BP is affected by a short-term vigorous training camp even in highly trained elite endurance athletes presumably due to a greater training volume compared to usual.

Keywords: aortic blood pressure, pulse wave analysis, endurance training, vigorous training, athletic conditioning

INTRODUCTION

There is a widely held notion that the central arterial pressure waveform is synthesized by the overlapped reflection waves returning from the periphery (mainly lower body) on the incident wave in phase; therefore, there are disparities between aortic and peripheral BP waveforms (Nichols and McDonald, 2011). Importantly, aortic BP is more strongly related to concentric left ventricular geometry than brachial BP (Roman et al., 2007). Furthermore, systolic BP is strongly related to left ventricular hypertrophy, and pulse pressure is strongly related to vascular stiffening (Roman et al., 2007, 2010). Thus, assessment of aortic BP could be an indicator of cardiac and vascular condition.

The beneficial effects of endurance exercise at a moderate intensity on the cardiovascular system are well recognized (Thompson et al., 2003; Seals et al., 2008; Rowe et al., 2014). On the other hand, the unfavorable effects of cardiovascular system including higher aortic stiffness and aortic BP have been confirmed among highly endurance-trained populations who participate in prolonged intense exercise events, especially marathons running (Scharhag et al., 2005; Vlachopoulos et al., 2010) and ultramarathons running (Knez et al., 2006; Burr et al., 2014) compared with age-matched physically active peers. However, the potential genetic influences in the aforementioned results cannot be completely ruled out due to a cross-sectional study design (Scharhag et al., 2005; Knez et al., 2006; Vlachopoulos et al., 2010; Burr et al., 2014). Vlachopoulos et al. (2010) and Scharhag et al. (2005) observed that peripheral and aortic BP and pulse pressure were significantly reduced 24 h after a marathon running race (Scharhag et al., 2005; Vlachopoulos et al., 2010), but this response seems to reflect post-exercise hypotension (Halliwill, 2001). Thus, the effect of high intense exercise training (e.g., repetition of intense endurance exercise bouts) on the aortic BP and pulse pressure is still unknown.

We previously reported that in well-trained male collegiate endurance runners, systemic arterial stiffness increased after a 7-day intense endurance training camp (Tomoto et al., 2015). Since arterial stiffening promotes early return of the reflected wave from peripheral to the heart and increases aortic BP (Nichols and McDonald, 2011), we hypothesized that the arterial stiffening induced by intense endurance training may cause to amplify the aortic arterial pressure waveform. As a follow-up study, the purpose of this study was to determine the effect of intense endurance exercise bouts to aortic BP.

METHODS

We recruited the subjects from national ranked *Ekiden relay race* team in Japan. We studied a total of 36 well-trained male collegiate endurance runners. The average of their official best times for a 5,000-m race was $14'28'' \pm 0'17''$ (mean ± SD). All of the subjects were healthy, normotensive (<140/90 mmHg), non-obese (Body mass index, BMI<25 kg/m^2), nonsmokers, who were free of medication as well as overt chronic heart and lung disease as assessed by their medical histories. None of the subjects were taking cardiovascular-acting medication. This study was reviewed and approved by the Institutional Review Board (Toyo University: 2012-R-04). Additionally, all procedures conformed to the ethical guidelines of the Helsinki Declaration. All subjects provided informed written consent prior to participation.

All measurements were performed at the same time of the day on the first day of the 7-day training camp and the day after the camp ended. Each subject fasted overnight prior to all measurements. Aortic and brachial hemodynamic parameters were recorded after at least 15 min supine-position rest in a quiet air-conditioned room (24–25°C). Subjects abstained from alcohol for 24 h and caffeine for 12 h prior to the experiment. Electrocardiogram (ECG), left carotid arterial pressure waveforms (via applanation tonometry sensor), and brachial BP (via oscillometric sensors) were simultaneously measured using a vascular function-screening device (form PWV/ABI, Omron-Colin, Kyoto, Japan). Carotid arterial pressure waveforms were transferred into aortic pressure waveforms by pulse wave analysis software involving a validated generalized transfer function (SphygmoCor software, AtCor Medical, Sydney, Australia) (**Figure 1**). The aortic hemodynamic parameters including aortic systolic BP, pulse pressure, augmentation pressure (AP), augmentation index (Alx), Alx corrected for heart rate at 75 beats per minutes (AIx_{75}), time to wave reflection (T_R), tension time index (TTI), diastolic time index (DTI), and sub-endocardial viability ratio (SEVR) were computed as previously reported (Vlachopoulos et al., 2010).

The 7-day camp was conducted in August (summer season). Although all subject engaged in regular long distance running, the target training distance during the 7-day camp was longer (26 km/day) than the weekly mandatory training distance. The target running distance the week before the camp was 13 km/day. To accomplish such a long distance, subjects participated in three practice sessions per day; 1st session (5:30–7:30), athletes mainly performed long distance running (group, individual, tempo running); 2nd session (8:30–12:30) consisted of jogging, basic core, and lower body strength training; 3rd session (14:00–18:30) consisted mainly of speed development training such as repetition of 400- and 1,000-m sprints. During the camp, all subjects were required to participate all practice sessions, and their schedules were strictly controlled, especially practice duration, meal times, and sleep.

To determine the effect of the intervention on the hemodynamic parameters, repeated measures analysis of variance was performed. In the case of a significant *F*-value, a post hoc test (the Bonferroni method) was performed to identify significant differences in the mean values of interest. For simple correlation analysis as well as to identify the effect of training distance on aortic and brachial BP, three subjects who did not engage any running practice during the camp were excluded due to lower leg injuries. These three subjects trained on the same schedule as others and performed stationary bike training instead of running. Data were reported as the mean ± SD. All comparisons were based on a 95% confidence limit with $P < 0.05$ considered statistically significant.

RESULTS

After the camp, the athletes were divided into two groups: the accomplished and unaccomplished group. The accomplished group ($n = 24$) achieved the daily and overall target, while the unaccomplished group ($n = 12$) did not complete the training menu due to deconditioning during the camp. The accomplished group constantly completed all training menu, whereas the unaccomplished group mainly engaged to long distance jogging and basic core and lower body strength training without speed development training (e.g. repetition of 400- and 1,000-m sprints). During the camp, the accomplished group completed a longer training distance than the unaccomplished group (31 ± 3 km/day vs. 13 ± 10 km/day, $P < 0.001$). The completed training distance in the accomplished group was approximately 2.5 times longer than 1 week before the camp. **Table 1** shows the physical characteristics and hemodynamic parameters before and after the camp. There was no significant group-difference in either physical characteristics or hemodynamic parameters prior to the camp. After the camp, excessive body weight loss, an indicator of dehydration, was not observed. The heart rate, brachial BP, aortic AP,

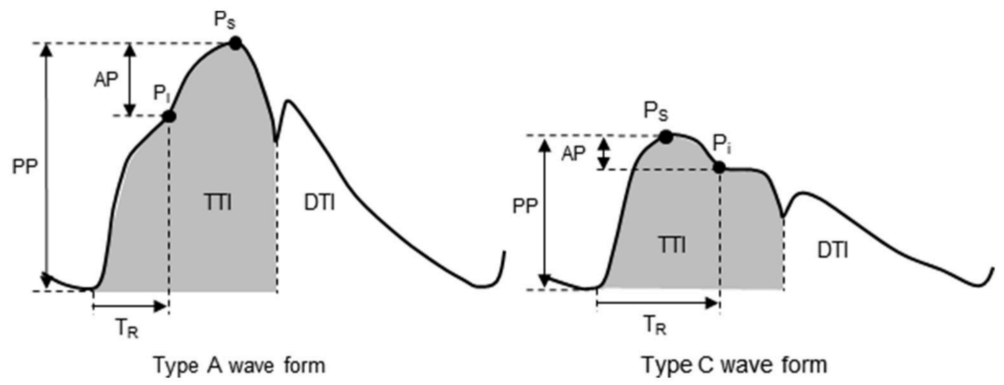

FIGURE 1 | Aortic pulse wave analysis. Type A waveform: reflecting wave during early systole produces an augmented systolic pressure. Type C waveform: reflecting wave during late systole produces a longer T_R and Pi after Ps. AP, augmentation pressure; DTI, diastolic tension index; Pi, incident pressure from a reflecting pressure wave; PP, pulse pressure; Ps, systolic pressure; T_R, round-trip travel time of the reflecting pressure wave; TTI, tension-time index.

TABLE 1 | Physical characteristics and hemodynamic variables in unaccomplished and accomplished training group before and after the camp.

	Unaccomplished group (n = 12)		**Accomplished group (n = 24)**	
	Before	**After**	**Before**	**After**
Height, cm	171 ± 5	–	171 ± 5	–
Weight, kg	58 ± 5	58 ± 5	58 ± 4	58 ± 4
Heart Rate, bpm	48 ± 5	48 ± 7	47 ± 5	48 ± 5
Brachial systolic BP, mmHg	109 ± 4	109 ± 4	110 ± 8	112 ± 8
Brachial Mean BP, mmHg	76 ± 3	75 ± 3	76 ± 6	78 ± 6
Brachial diastolic BP, mmHg	60 ± 4	58 ± 4	59 ± 6	60 ± 6
Brachial PP, mmHg	49 ± 4	50 ± 5	51 ± 4	52 ± 5
Aortic AP, mmHg	−2 ± 6	0 ± 4	0 ± 5	1 ± 6
AIx, %	−4 ± 12	0 ± 9	−1 ± 11	3 ± 11
AIx_{75}, %	−17 ± 13	−13 ± 9	−14 ± 11	−11 ± 11
T_R, msec	173 ± 10	175 ± 7	172 ± 10	167 ± 11*
TTI, mmHg*ms	1,399 ± 146	1,366 ± 159	1,342 ± 168	1,434 ± 134*
DTI, mmHg*ms	3,096 ± 172	3,129 ± 215	3,115 ± 290	3,186 ± 316
SEVR, %	223 ± 27	233 ± 40	235 ± 31	224 ± 27

*Data are mean ± SD. BP, blood pressure; MAP, mean arterial pressure; PP, pulse pressure; AP, augmentation pressure; AIx, augmentation index; AIx_{75}, AIx corrected for heart rate at 75 beats per minutes; T_R, round-trip travel time of the pressure wave from the heart to the peripheral reflected sites; TTI, time tension index; DTI, diastolic tension time integral; SEVR, subendocarial viability ratio. *$P < 0.05$ vs. before the camp.*

AIx, and AIx_{75} were unchanged in both groups. The aortic systolic BP and pulse pressure significantly increased after the camp in the accomplished group ($P < 0.001$) but not in the unaccomplished group (**Figure 2**). In the accomplished group, T_R shortened and TTI increased significantly ($P < 0.01$), whereas DTI and SEVR did not significantly change after the camp. The average training distance during the camp was not significantly correlated with the changes in brachial systolic BP and pulse pressure, whereas changes in aortic hemodynamic measures were correlated with the average training distance: aortic systolic BP, pulse pressure, TTI, and SEVR (**Figure 3**). Individual changes in T_R did not correlate with corresponding changes in aortic hemodynamic measures: aortic systolic BP ($r = -0.230$, $P = 0.166$); aortic pulse pressure ($r = -0.055$, $P = 0.750$); aortic AP ($r = 0.012$, $P = 0.945$), AIx ($r = -0.016$, $P = 0.929$), and AIx_{75} ($r = -0.064$, $P = 0.725$); TTI ($r = -0.203$, $P = 0.235$); DTI ($r = 0.056$, $P = 0.746$); SEVR ($r = 0.250$, $P = 0.142$).

DISCUSSION

The primary findings from the present study are as flows. First, aortic systolic BP, pulse pressure, and tension-time index (TTI, a surrogate index of the myocardial oxygen demand) were significantly elevated after the camp in the accomplished group but not in the unaccomplished group, whereas the brachial BP remained unchanged in both groups. Secondly, the average daily training distance was significantly correlated with the changes in aortic systolic BP, pulse pressure, and TTI. These results suggest that aortic BP is affected by a short-term vigorous training camp

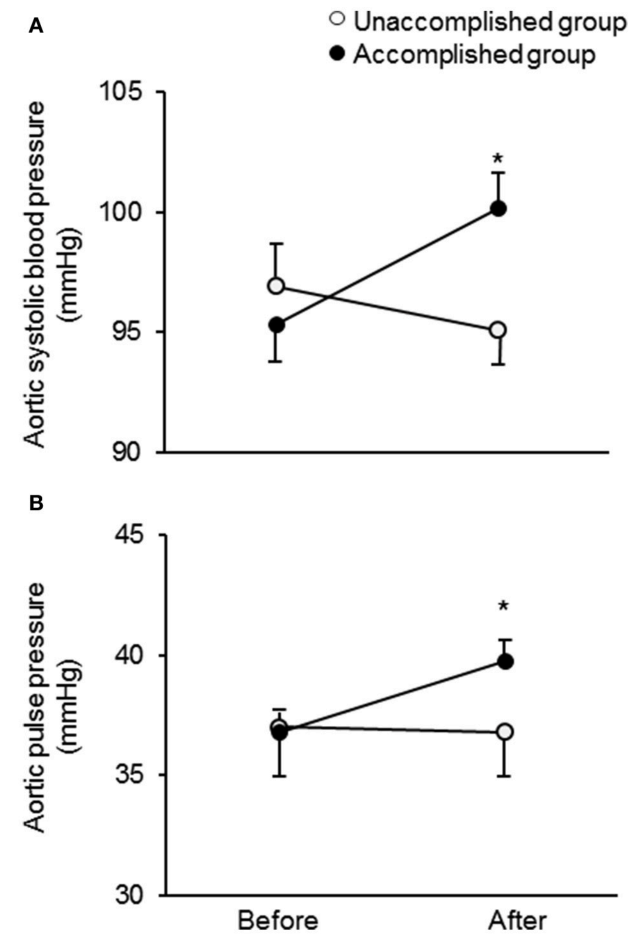

FIGURE 2 | Change in aortic systolic blood pressure **(A)** and pulse pressure **(B)** in the unaccomplished and accomplished groups before and after the camp. *$P < 0.05$ vs. before the camp.

even in highly trained elite endurance athletes partly due to a greater training volume compared to usual.

To the best of our knowledge, this is the first study demonstrating the acute elevation of aortic systolic BP and pulse pressure in elite endurance athletes after short-term endurance training camp characterized by a greater-than-normal training volume. Such changes were associated with a proximally greater than twice longer running distance compared with 1 week before the camp. In addition, individual changes in TTI, a surrogate index of oxygen demand, was positively correlated and SEVR, surrogate indices of myocardial oxygen consumption (Sarnoff et al., 1958) and sub-endocardial perfusion (Buckberg et al., 1972), was correlated negatively with the training distance during the camp. These results suggest that increased training volume with short-term may lead imbalance of myocardial oxygen demand and supply and cause of myocardial fatigue. Our findings could expand the evidence from the cross-sectional investigation that highly trained marathon runners have a higher aortic BP compared with age-matched recreationally active control subjects (Vlachopoulos et al., 2010). More importantly, the training camp did not significantly alter the peripheral BP, and individual changes in peripheral BP were not associated with the training distance during the camp. These results suggest that aortic hemodynamic measures are more sensitive than peripheral BP to acutely increased training volume. To confirm these findings, prospective data linking aortic BP response to chronic overtraining are needed.

The aortic pressure wave may be augmented by overlapping the early return and high amplitude of the reflected wave from the periphery (mainly from lower body) to the proximal aorta on the forward traveling wave generated by the LV ejection in-phase (Nichols and McDonald, 2011). In the present study, T_R (a surrogate index of aortic pulse wave velocity) significantly correlated with other aortic hemodynamic measures such as aortic systolic BP and PP. Therefore, increases in aortic systolic BP and PP could not be explained by the early return of the reflected wave from peripheral to the heart. In this context, contrary to the traditional wave theory (Nichols and McDonald, 2011), recent studies suggest that the reflected wave component of arterial hemodynamics does not contribute to augmented central pressure (Schultz et al., 2015; van Mil et al., 2016). Furthermore, it has been also reported that the reflected wave might become diminished until in the proximal aorta, and it no longer possible to identify contributions to central pressure augmentation (Davies et al., 2012). Growing evidence suggests that major determinants of central BP waveform may be the incident waves arising from left ventricular ejection and proximal aortic compliance rather than the wave reflection (Sharman et al., 2009; Davies et al., 2010; Schultz et al., 2014).

The changes in central hemodynamic parameters in this study were potentially impacted by repeated mechanical stress from the heart, inflammatory state from muscle damage, and heart accumulation from prolonged exercise training during summer. First, repeated and particularly excessive stress imposed on the elastic elements of the aortic wall may be a cause of their mechanical fatigue which leads to elevating aortic BP (Nichols and McDonald, 2011). Secondary, aortic BP is affected by inflammatory state common observed in marathon runner after the race (Knez et al., 2006, 2007). It is plausible that the vigorous training-induced muscle damage and systemic inflammation may contribute to elevating aortic BP (Jee et al., 2013). In the present study, the participants of the camp practiced not only on flat track conditions but also on up-and downhill courses; thus, a large amount of exercise stress—especially eccentric contractions during downhill running—was given to the muscle. Furthermore, the 7-day training camp was conducted on summer, thus, the prolonged exercise in the heat causes greater hyperthermia that may yield heat acclimation. Further investigation to clarify the underlying mechanisms for sustained aortic arterial pressure elevation following vigorous intensity exercise training, especially during heat stress, is needed.

Several experimental considerations should be noted. The primary issue is the lack of recorded training intensity, such as heart rate during exercise. For example, by multiplying the duration of a training session by the average heart rate

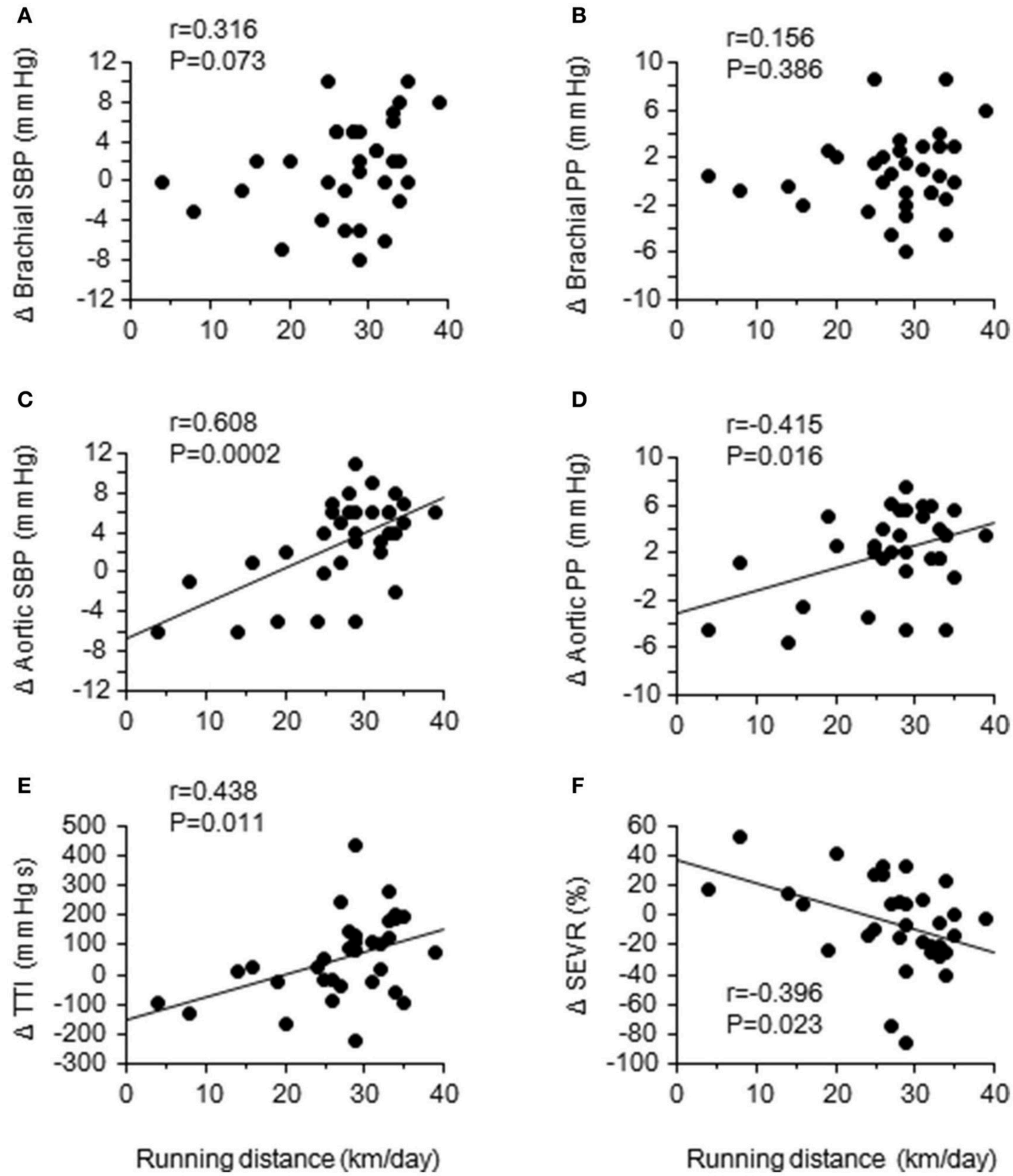

FIGURE 3 | Relationships between the daily training distance and changes in brachial and aortic hemodynamics: brachial and aortic systolic blood pressure (SBP) **(A,C)** and pulse pressure (PP) **(B,D)**; aortic tension-time index (TTI) **(E)**; sub-endocardial viability ratio (SEVR) **(F)**.

achieved during a session (i.e., training impulse; Macdougall et al., 1982), the training stimulus could be quantified in detail. In addition, we did not evaluate the concomitant changes in biochemical parameters (i.e., inflammation biomarker) and autonomic nervous activity. Measuring these parameters may yield insight on the mechanism of the increased aortic systolic BP after the training camp.

Training programs for highly trained athletes are planned with the repetition in the training cycle composed of intense training periods followed by shorter recovery periods, such as the repetition of over-reaching and super-compensation. The imbalance between training volume/intensity and recovery can lead to an advanced fatigue state (i.e., overtraining syndrome). Therefore, useful (e.g., sensitive) markers to detect fatigue are needed to prevent and manage overtraining for not only athletes but also coaches. Since the strength of this study was a field study with measured hemodynamics parameters in controlled condition among well-trained endurance athletes before and after the camp, the results of this study may provide the consideration of planning short-term summer training camps.

In conclusion, in highly-trained elite endurance athletes, the aortic systolic BP and pulse pressure increases acutely without concomitant elevations in brachial BP after a 7-day training camp characterized by a greater training volume compared with regular training. These alterations might be associated with a greater training volume.

AUTHOR CONTRIBUTIONS

TT, JS, AH, TI, and SO: Decided conception and design of research; performed experiments; analyzed data; TT, JS, SM, and SO: Interpreted results of experiments; TT and JS: Prepared figures; TT, JS, and SO: Drafted manuscripts; TT, JS, AH, TI, SM, and SO: Approved final version of manuscripts.

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The Training Characteristics of the World's Most Successful Female Cross-Country Skier

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The main aim of this study was to investigate the training characteristics of the most successful female cross-country skier ever during the best period of her career. The participant won six gold medals at the Olympic Games, 18 gold medals at the World Championship, and 110 World Cup victories. Day-to-day training diary data, interviews, and physiological tests were analyzed. Training data was systemized by training form (endurance, strength, and speed), intensity [low- (LIT), moderate- (MIT), and high-intensity training (HIT)], and mode (running, cycling, and skiing/roller skiing), followed by a division into different periodization phases. Specific sessions utilized in the various periodization periods and the day-to-day periodization of training, in connection with altitude camps and tapering toward major championships, were also analyzed. Following a 12-year nonlinear increase in training load, the annual training volume during the five consecutive successful years stabilized at 937 ± 25 h, distributed across 543 ± 9 sessions. During these 5 years, total training time was distributed as 90.6% endurance-, 8.0% strength-, and 1.4% speed-training, with endurance-training time consisting of 92.3 ± 0.3% LIT, 2.9 ± 0.5% MIT, and 4.8 ± 0.5% HIT. Total LIT-time consisted of 21% warm-up, 14% sessions <90 min, and 65% long-duration sessions >90 min. While the total number of LIT sessions remained stable across phases (32 sessions), total LIT-time was reduced from GP (76 h/month) to SP (68 h/month) and CP (55 h/month). MIT-time decreased from GP (2.8 h/month) to SP (2.2 h/month) and CP (1 h/month). HIT-time increased from GP (2.8 h/month) to SP (3.2 h/month) and CP (4.7 h/month). Altitude training accounted for 18–25% of annual training volume and performed across relatively short training camps (≤16 days) with a clear reduction of HIT training, but increased total and LIT volume compared to sea-level training. Training before international championships included a 2-week increase in LIT and strength volume followed by a gradual reduction of training volume and increased HIT during the last week. This study provides unique data on the world's most successful female cross-country skier's long-term training process, including novel information about the distribution of and interplay between sessions of different forms, intensities, and exercise modes throughout the annual season.

Keywords: altitude training, endurance training, high-intensity training, performance, periodization, speed training, strength training, tapering

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INTRODUCTION

Cross-country (XC) skiers optimize their training to perform in competitions ranging from multiple 3-min sprint races to prolonged endurance races lasting up to 2 h. These competitions are performed across varying terrain while changing between the different sub-techniques in classic and skating (Sandbakk and Holmberg, 2017). Although the average aerobic energy contribution is 70–75% in sprint races and 85–95% for longer distances, the race format is interval-based, with increased effort in uphill terrain and lower intensities downhill (Norman et al., 1989; Sandbakk et al., 2011a; Sandbakk and Holmberg, 2017). Furthermore, the majority of competitions involve mass-starts in which sprint ability is critical in determining the final result. Accordingly, high aerobic capacity is of crucial importance in XC skiing, as reflected by world-class XC skiers' high VO_{2max} values (>80 and ∼70 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ for men and women, respectively) (Saltin and Astrand, 1967; Ingjer, 1991; Sandbakk et al., 2011b, 2016; Tonnessen et al., 2015a). However, XC skiers also need the ability to rapidly elevate their peak oxygen uptake, utilize a high fraction of their VO_{2max} in all of the sub-techniques, and have well-developed skiing efficiency and anaerobic capacity (Sandbakk and Holmberg, 2017). Unique for XC skiing, both training and competitions involve large fluctuations in speed, work rate, and metabolic intensity, in addition to a varying load on the upper and lower body with the different training modes and sub-techniques utilized. Hence, the training of XC skiers is made up of a sophisticated puzzle of training sessions of different forms, intensities, and exercise modes that has not yet been examined in detail.

World-class XC skiers have previously reported 800–950 annual training hours (Tonnessen et al., 2014; Sandbakk et al., 2016). Of the total annual training volume, >90% of elite XC skiers' has been reported to be endurance training, with the remaining ∼10% performed as strength or speed work (Sandbakk et al., 2011b, 2016; Tonnessen et al., 2014). These studies showed a pattern of endurance training time distributed as 88–91% low-intensity training (LIT, $< VT_1$ aerobic threshold), 3–7% moderate-intensity (MIT, $VT_1 < > VT_2$ anaerobic threshold), and 5–8% high-intensity training (HIT, $>VT_2$). As also shown in other endurance sports (Stoggl and Sperlich, 2015), a pyramidal training pattern is often found during the preparation period, whereas more polarized training is done in the competition phase.

Approximately 60% of the total training time is performed during the general preparation period between May and October. This period typically includes high volumes of LIT and 50–60% of the endurance-training conducted as sport-specific exercise (e.g., roller skiing and skiing), with the remainder mainly performed as running (Tonnessen et al., 2014; Sandbakk et al., 2016). The remaining 40% of annual training is performed during the specific preparation and competition phase, with decreased total volume, increased amount of HIT (including 30–40 competitions) and higher amount of sport-specific activity forms (Sandbakk and Holmberg, 2017). While the intensity distribution and use of activity forms during different phases of the year are well covered by several retrospective studies (Sandbakk et al., 2011b, 2016; Tonnessen et al., 2014), the design of specific sessions within the different zones and modes are not well illustrated in the current literature.

In terms of periodization, most XC skiers use a traditional model, alternating between high- and low-volume weeks while keeping the number of MIT and HIT sessions relatively stable (two to three sessions per week; Tonnessen et al., 2014). However, some athletes organize the training in blocks with increased focus on developing specific capacities over shorter periods (Sandbakk and Holmberg, 2017). Altitude training represents a significant portion of world-class XC skier training and is an important piece of the periodization puzzle (Sandbakk et al., 2016). The main aim of these altitude training camps (living at ∼1,800–2,000 m above sea-level and training at 1,000–3,000 m) is mainly to positively stimulate hematological parameters, and thereby improve performance during the subsequent training and/or competition period (Millet et al., 2010). However, in XC skiing, altitude training also provides an opportunity for many hours of skiing on snow throughout the dry-land training period (Sandbakk and Holmberg, 2017). Although training at altitude has been used by endurance athletes for several decades, accurate descriptions of the micro periodization of successful athletes is lacking in the literature.

To ensure peak performance, a typical tapering approach has been to perform 2–4 weeks of overload training, followed by 1–3 weeks with decreased load (Hellard et al., 2013). Bosquet et al. (2007) reported that performance improvements are highly sensitive to reductions in training volume and that the optimal range of volume reduction is 41–60%, without substantial decreases in training frequency, compared to the pre-tapering training. However, a recent study (Tonnessen et al., 2014) observed that gold medal winning athletes in XC skiing and biathlon used a more modest and progressive reduction in training volume, with a relatively small reduction during the last weeks prior to gold-medal performance. The authors speculate that this progressive tapering strategy could be ideal in sports with a dense competition schedule, as is the case in XC skiing. However, the study reports large individual differences in tapering behavior and does not consider the specific sessions utilized during the final phases of the taper. Thus, tapering behavior in world-class endurance athletes is lacking, particularly in athletes who have attained repeated success in major championships.

The training of world-class XC skiers involves manipulation of variables such as different training forms (endurance, strength, and speed), exercise modes (loading of the upper and/or lower body), session organization (continuous or interval), and varying terrain, making it more complex than many other endurance sports. This makes it particularly challenging to investigate at a group level. Case studies allow us to investigate every piece of the training in detail and expand our understanding of champion performance development. Earlier case studies of high-level endurance athletes have focused on physiological test data (Jones, 1998, 2006; Bell et al., 2017) or short-term training studies (Stellingwerf, 2012; Mujika, 2014; Manunzio et al., 2016; Ronnestad et al., 2017). Only a minority of studies consist of longitudinal training data spanning several years, and the majority of these focus on male subjects (Ingham et al., 2012; Tjelta, 2013; Bourgois et al., 2014; Tjelta et al., 2014; Pinot and Grappe, 2015).

Therefore, the primary aim of this study was to investigate the training characteristics of the most successful female XC skier ever during the best period of her career, including the day-to-day periodization of her training in connection with altitude camps and tapering toward major international competitions. In order to interpret these findings in the perspective of her long-term development process, the secondary aim was to characterize her longitudinal training patterns over 17 years.

METHODS

Participant

The participant (born in 1980) is the most successful female competitor of all time in the winter Olympics and Nordic skiing World Championships. This includes six Olympic gold medals (four individual, two team), 18 gold medals from the FIS World Ski Championship (12 individual, six team), 110 individual FIS World-Cup victories, and four wins of the overall FIS World Cup (FIS, 2017). The study was evaluated by the regional ethics committee of mid-Norway, and approved by the Norwegian Social Science Data Services (NSD). Written informed consent was obtained from the participant for the publication of this study, which was performed according to the Helsinki declarations.

Overall Design

To give both comprehensive understanding of and detailed insight into the athlete's training, the study was divided into two parts (1) investigations of the participant's longitudinal training, performance, and test data spanning 17 years from the age of 20 to 37 years old (2000–2017); and (2) detailed investigations of the training during five consecutive successful seasons from the age of 30 to 35 years old (2010–2015), including four international championships with nine individual gold medals.

Performance Data

Performance data for each year was calculated using both race results and the International Ski Federation's (FIS) ranking points from all individual distance and sprint competitions, including World Cup competitions, the Olympic Games, and the FIS World championships (FIS, 2017).

Physiological Testing

The participant underwent regular VO_{2max} and lactate profile testing (test results presented in **Table 1**). No physiological tests were performed during the competition period (CP), and the presented results therefore represent tests from May or June (the start of the general preparation period; GP) and October or November (the start of the specific preparation period: SP). All physiological testing during the period was conducted at the Norwegian Olympic Sports Centre, primarily supervised by the same exercise physiologist. The apparatus and testing procedures used during the lactate profile and VO_{2max} test are previously described (Ingjer, 1991; Tonnessen et al., 2015a). Anaerobic threshold (AT) was determined during treadmill running at 10.5% incline using a graded protocol, including 4–6 periods of 5-min stages with stepwise 1-km/h increases in workload (Enoksen et al., 2011). The same treadmill (Woodway Gmbh, 124 Weil am Rhein, Germany) was used at all tests and lactate concentration was measured from the fingertip by an YSI 1500 sport lactate analyzer (YSI, Ohio, USA) directly after completion of each stage. VO_2 was recorded between the third and fourth minute at each stage using an Oxycon Pro (Jaeger-Toennis, Wurtzburg, Germany) metabolic test system. AT was determined at the workload corresponding to 1.5 mmol/1 higher lactate concentration than the baseline value (averaged over the two first measurements). Total, lean, and fat mass were analyzed for the legs, trunk, arms, and head using dual-energy X-ray absorptiometry (DXA) (Encore 2007, Version 11.4, General Electric Medical Systems, Madison, WI, USA), and presented in absolute values (**Table 1**).

Training Monitoring

The participant recorded her day-to-day training in digital diaries designed by the Norwegian Ski Association and the Norwegian Olympic Federation. The training recorded for each session included total training time distributed across training form (endurance, strength, and sprint), activity form (skiing, roller-skiing, running, cycling, etc.), and intensity zone. Specific comments regarding session details were also recorded.

To register the endurance-training intensity, the five-zone intensity scale developed by the Norwegian Olympic Federation was used, which has been reported to provide a valid and accurate measurement of the duration and intensity of training by XC skiers (Sylta et al., 2014a). However, since these zone boundaries do not clearly correspond with underlying physiological events (Boulay et al., 1997), we used a three zone scale based on the ventilatory changes corresponding to the first- and second-lactate turning point (Boulay et al., 1997; Seiler and Kjerland, 2006). LIT refers to a training intensity below the first lactate threshold (LT^1) (<2 mM blood lactate, 60–82% of maximal heart rate; HR_{max}). Moderate-intensity training (MIT) refers to an intensity between LT^1 and LT^2 (2–4 mM blood lactate, 82–87% of HR_{max}). High-intensity training (HIT) refers to an intensity above LT^2 (>4 mM blood lactate, >87% of HR_{max}) (Seiler and Kjerland, 2006). Standardized intensity scales do not take into account the individual or activity-specific variation, such as the tendency for maximal steady-state concentrations of blood lactate tending to be higher in activities activating less muscle mass (Beneke and von Duvillard, 1996; Beneke et al., 2001). Hence, the participant in this study tailored her intensity zones in accordance with both test results and her own experience. Her self-reported intensity zones are presented in **Table 2**.

Registration and Systematization of Training Data

To register training time, the participant used a combination of the session-goal approach and time in training zone often called a *modified session-goal approach,* described in detail by (Sylta et al., 2014b). The participant registered endurance training by allocating the time of the different parts of the sessions (e.g., warm-up, intervals, and cool-down) into intensity zones

TABLE 1 | Physiological characteristics of the world's most successful female cross-country skier during the successful period from 2010 to 2015.

	2010		2011		2012		2013		2014		Mean ± SD
	GP1	GP2	GP1	GP2	GP1	GP2	GP1	GP2	GP1	GP2	
Age (year)	30	30	31	31	32	32	33	33	34	34	32.0 ± 1.5
Body height (cm)	167	167	167	167	167	167	167	167	167	167	167.0 ± 0.0
Body mass (kg)	65.4	64.6	64.9	64.2	65.7	64.6	65.2	65.2	64.1	64.0	64.8 ± 0.6
Body mass index ($kg·m^{-2}$)	23.5	23.2	23.3	23.0	23.6	23.2	23.4	23.4	23.0	22.9	23.2 ± 0.2
Lean body mass (kg)	–	–	–	–	–	54.9	54.5	–	54.6	55.0	54.8 ± 0.2
Lean upper body mass (kg)	–	–	–	–	–	35.0	34.1	–	34.0	34.5	34.4 ± 0.5
Lean lower body mass (kg)	–	–	–	–	–	18.3	17.4	–	17.5	17.6	17.7 ± 0.4
Total body fat (%)	–	–	–	–	–	14.8	15.2	–	14.2	12.8	14.3 ± 1.1
VO_{2max} ($L·min^{-1}$)*	4.23	4.49	4.31	4.39	4.47	4.52	4.33	4.37	4.42	–	4.39 ± 0.1
VO_{2max} ($ml·kg^{-1}·min^{-1}$)*	64.7	69.5	66.4	68.4	68.0	70.0	66.4	66.7	69.0	–	67.7 ± 1.7
$VO_{2@AT}$ ($ml·kg^{-1}·min^{-1}$)*	58.9	61.1	57.0	59.2	60.7	63.6	58.7	61.0	59.4	60.8	60.0 ± 1.8
$V_{@AT}$ (km/h)*	9.8	10.9	10.3	10.7	10.8	10.9	10.6	10.8	10.7	11.2	10.7 ± 0.4

*VO_{2max}, maximal oxygen uptake; AT, estimated anaerobic threshold; $VO_{2@AT}$ oxygen uptake at the anaerobic threshold (running); V@AT, velocity at the anaerobic threshold; GP1, general preparation period one; GP2, general preparation period two; *, gradient of treadmill 10.5%.*

TABLE 2 | Self-reported intensity zones presented as maximal, minimal and most commonly used (target) heart rates in the specific training zones, as well as the average rating of perceived exertion across the different categories of endurance sessions for the world's most successful female cross-country skier.

Intensity zones	HR zones			RPE	Session categories
	Min Beat · min^{-1} (% HR_{max})	Target Beat · min^{-1} (% HR_{max})	Max Beat · min^{-1} (% HR_{max})		
LIT*	115 (67)	115–130 (67–75)	149 (86)	11	Warm up and cool down** Short-duration session < 50 min Medium-duration session [50–90 min> Long-duration session [90–150 min > Very long-duration session ≥ 150 min
MIT	150 (87)	155–160 (89–92)	160 (92)	15	Continuous training Intervals with periods from 10 to 15 min Intervals with periods from 6 to 10 min
HIT	161 (93)	161–170 (93–98)	173 (100)	19	Continuous training# Intervals with periods from 4 to 7 min Intervals with periods < 4 min##

LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training; RPE, Rating of perceived exertion (BORG scale, 6–20).
When sprints were integrated into LIT sessions, sprint time (including 1-2 min recovery after each sprint) was subtracted from the overall duration of the session. The remaining time was categorized as LIT.
**The category includes LIT performed as warm up or cool down in connection with MIT, HIT and strength sessions.*
Including distance competitions.
Including sprint competitions.

based on actual HR registration supported by external load, lactate measurements, and self-perceived exertion. For MIT and HIT sessions performed as intervals, the time in the MIT/HIT zone was registered from the beginning of the first interval to the end of the last interval, including recovery periods. Strength and speed training was registered from the start to the finish of the specific strength/speed/jump part of the session, including recovery periods. When speed training was integrated into LIT sessions, 2 min per sprint was registered as speed training.

All data from training diaries were systematically analyzed session-by-session by researchers from the current research group. Total training time and frequency of sessions were distributed in line with "the training distribution method" previously described (Tonnessen et al., 2014). All endurance sessions were categorized based on duration and/or design, as presented in **Table 2**.

Periodization Phases

General training data are either presented as annual training characteristics or divided into different periodization phases, as presented in **Table 3**. The day-to-day periodization of training before, during, and after altitude camps is quantified based on the final 2 weeks prior to altitude training, the first 2 weeks of altitude training, and the 2 weeks after the altitude camp in October. The training during and after the second week

TABLE 3 | The division of periodization phases across the annual training cycle, including altitude- and peaking phases*.

Phase	Period in annual training cycle	Duration (days)
General preparation Period (GP)	May–October	184
General preparation Period 1 (GP1)	May–July	92
General preparation Period 2 (GP2)	August–October	92
Pre-altitude phase	*Day 14-1 before altitude camp*	*14*
Altitude phase	*Day 1-14 of the altitude camp*	*14*
After-altitude phase	*Day 1-14 after altitude camp*	*14*
Specific preparation period (SP)	November–December	61
Competition period (CP)	January–March	90
Pre-peaking Phase 1	*Day 42-29 before first championship event*	*14*
Pre-peaking Phase 2	*Day 28-15 before first championship event*	*14*
Peaking Phase	*Day 14-1 before first championship event*	*14*

April was defined as regeneration period and was not included in any of the other periods. However, training time in April is included in the calculation of the total annual training.

of the altitude camp in 2012 was excluded from the analysis because of illness. Tapering characteristics are quantified based on the six final weeks of training prior to the FIS World Championships in 2011, 2013, and 2015 and the Olympic Games in 2014.

Interviews

To track missing data, ensure compliance with the training diary commentaries, and verify the training intensity of different training sessions, two structured and one semi-structured interview with the participant were conducted during the data-analysis phase of this study.

Missing Data

Training information was lacking for March and April of the 2010/2011 season. Data for these months was calculated based on the years in which data was completely documented and modified based on training plans and an interview with the athlete. Sessions where information about session design was lacking (10% of MIT sessions and 3% of the HIT sessions) were only used in the time-in zone analyses.

Statistical Analyses

All data from the 2010–2015 period is presented as mean ± standard deviation (SD) of the five years. To calculate the monthly and weekly distribution of training, total training was divided by duration (days) of the specific phase and multiplied by 30.4 to determine monthly time/frequency (**Figures 2**, **3A–D**, **4A–C**) or by seven to determine the weekly time and frequency (**Table 4** and **Figures 5A,B**). All statistical analyses were carried out in Microsoft Office Excel 2013 (Microsoft, Redmond, WA, USA).

RESULTS

Longitudinal Training Characteristics

In total, 8,105 training sessions were analyzed during the period from 2000 to 2017. These sessions comprised of 7,642 workouts and 463 XC skiing competitions. Performance and training data during all 17 years are presented in **Figures 1A,B**. Total annual training volume increased by 80% (from 522 to 940 h) from the age of 20–35 (2000–2015). This a yearly progression of 30 ± 53 h and an increase from ∼10 to 18 weekly training hours. The relative distribution of endurance training into LIT/MIT/HIT was polarized, but to a lesser extent during the latter part of her career, i.e., ∼88/2/10 during the first part of her senior career (20–27 years old) and ∼92/3/5 during the latter part (28–35 years old). Subsequently, LIT volume increased from ∼430 h (20 years old) to ∼800 h (35 years old). The amount of MIT + HIT was ∼60 h during both the early (20–23 years old) and latter (29–35 years old) stage of her career, but was markedly higher (∼80 h) during a 5-year period from 23 to 28 caused by the use of extensive HIT blocks during the general preparation phase.

Training Characteristics of the Five Most Successful Seasons

During the five consecutive seasons, from May 2010 to April 2015, the participant achieved 107 individual podium places in international competitions, including Olympic Games, FIS World championships and FIS World Cup. This consisted of 63 individual World Cup victories, two gold medals from the 2014 Olympics and seven gold medals from the three World Championships. Annual ranking and FIS points in the abovementioned international races were 2.5 ± 0.8 (2.0 ± 0.8 in distance races and 3.4 ± 2 in sprint races) and 9.3 ± 3.0 (including distance races and sprint qualifications points), respectively.

Physiological tests (**Table 1**) showed an average VO_{2max} of 4.39 ± 0.09 ($L \cdot min^{-1}$) and 67.7 ± 1.7 ($ml \cdot kg^{-1} \cdot min^{-1}$) during the 5 years, with increased values from GP1 to GP2. VO_2 at AT was approximately 89% of VO_{2max}.

A total of 2,713 training sessions, performed in the period from May 2010 to April 2015 were categorized based on the detailed design of the session (**Table 3**). Total annual training volume was 937 ± 25 h, distributed across 543 ± 9 sessions. This consisted of 849 ± 18 h (91%) endurance training, 75 ± 21 h (8%) strength training and 14 ± 2 h (1%) speed training. Monthly and weekly training patterns during different phases of the annual cycle are presented in **Figure 2** and **Table 4**.

Endurance Training

Using the modified session goal approach, 92.3 ± 0.3% of total endurance training time was executed as LIT, 2.9 ± 0.5% as MIT and 4.8 ± 0.5% as HIT (including competitions). When all endurance sessions were categorized using the session goal method, the distribution was 76.1 ± 1.1% LIT sessions, 7.3 ± 1.2% MIT sessions and 16.6 ± 1.2% HIT sessions.

Annual LIT volume was 784 ± 10 h. Monthly LIT volume decreased from GP (76 h), to SP (68 h) and further to CP (55 h)

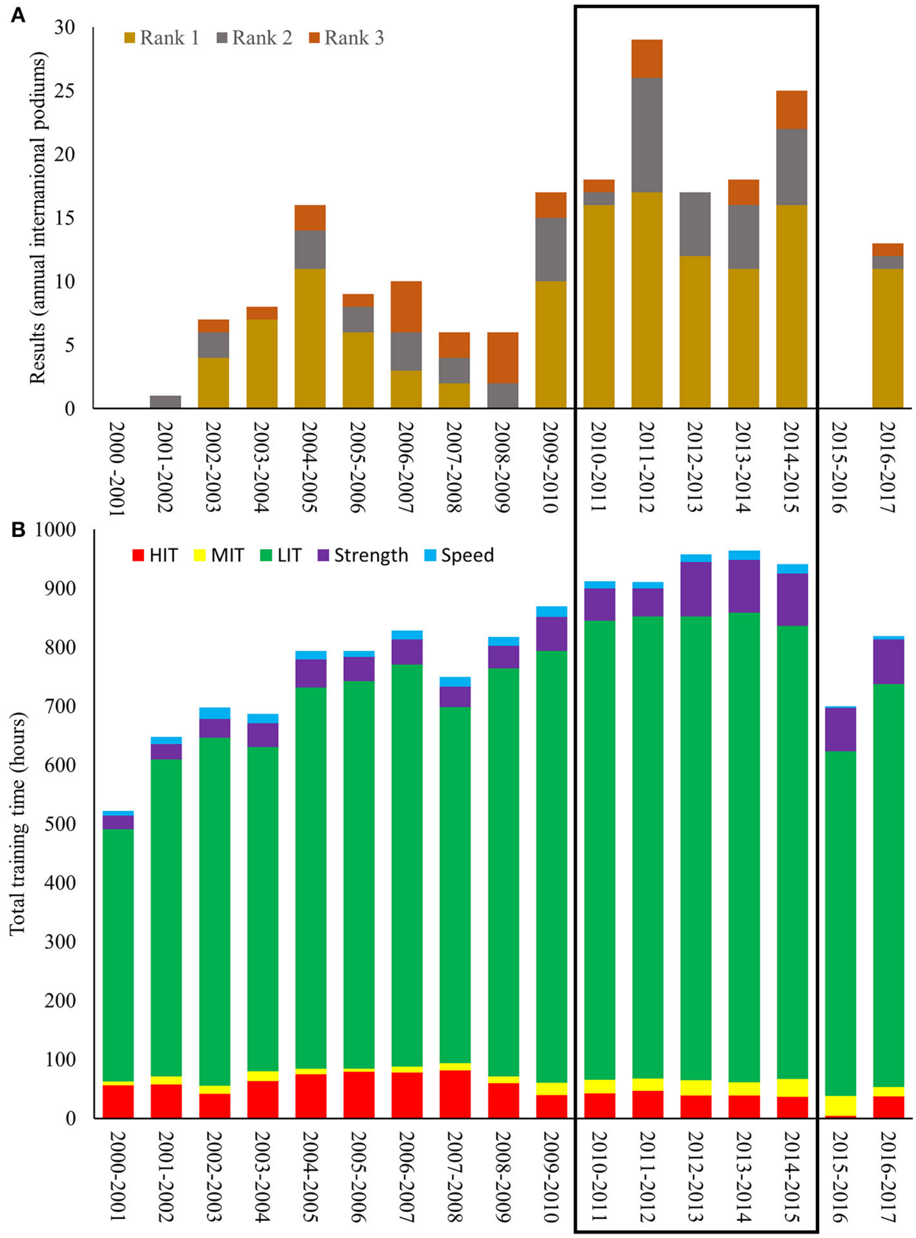

FIGURE 1 | (A,B) Annual top three performances **(A)** in international competitions and annual training characteristics **(B)** distributed into endurance (low-, moderate-, and high-intensity), strength and speed training during a 17-year period for the world's most successful female cross-country skier.

while the number of LIT sessions remained relatively stable across all phases (31.8 ± 1.6 sessions/month). Hence, the average duration of LIT sessions was reduced from GP (2.0 h) to SP (1.5 h) and CP (1.3 h). Total LIT time was distributed as 4% sessions < 50 min, 10% as sessions [50–90> min, 42% as sessions [90–150> min and 23% as sessions ≥150 min. The remaining 21% of LIT time was performed as warm-up or cool down in connection with MIT, HIT, or strength sessions. The number of LIT sessions in the different categories during the different phases are presented in **Figure 4A**.

Annual MIT volume was 24.6 ± 3.6 h. Monthly MIT volume decreased from GP (2.8 h) to SP (2.2 h) and further to CP (1.0 h). The monthly number of MIT sessions was relative stable across GP1, GP2, and SP (3.5 sessions), but decreased markedly in CP (2 sessions). Average duration of MIT sessions decreased from GP (0.8 h) to SP (0.7 h) and CP (0.5 h). The annual number of 35 ± 5 MIT sessions consisted of 20% continuous sessions, 48% interval sessions with interval-durations from 6 to 10> min, and 22% as interval sessions with interval-durations from 10 to 15 min. The most common MIT session was an interval session consisting of

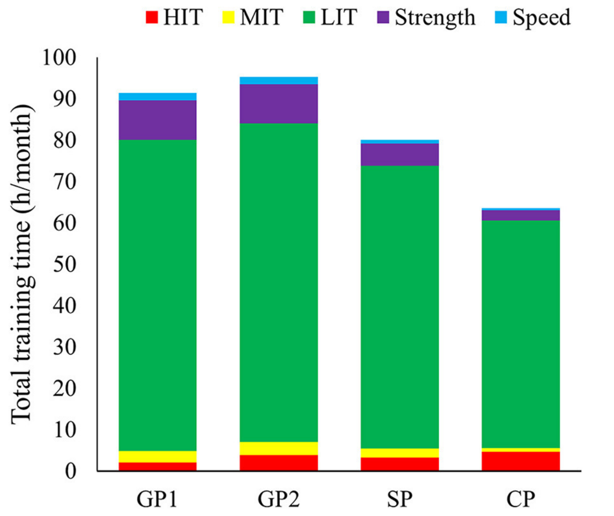

FIGURE 2 | Training distribution across phases during the successful 2010–2015 period distributed into endurance (low-, moderate-, and high-intensity), strength and speed training for the world's most successful female cross-country skier.

5 × 7–8 min working periods, with 1–2 min rest in between. The use of specific MIT sessions during different phases of the annual cycle is presented in **Figure 4B**.

Annual HIT volume was 40.4 ± 3.6 h. Monthly HIT volume increased from GP1 (2.0 h) to GP2 (3.7 h), was slightly reduced in SP (3.2 h) and then increased in CP (4.7 h). The monthly number of HIT sessions increased from GP1 (4.1 sessions) to GP2 (7.0 sessions), SP (8.2 sessions) and CP (9.2 sessions). Average duration of HIT sessions was approximately equal (0.5 h) across all phases except from SP (0.4 h). The number of annual competitions was 38.6 ± 6.3 (∼70% distance- and ∼30% sprint-competitions). Competition time increased from GP (0.5 h/month), to SP (1.6 h/month) and further to CP (3.1 h/month). Competitions accounted for 42 and 49% of total HIT time and number of HIT sessions, respectively. The annual number of 79 ± 8 HIT sessions consisted of 45% continuous sessions (including distance competitions), 38% interval training with interval-durations from 4 to 7 min and 14% intervals with interval-durations < 4 min (including sprint competitions). The most typical HIT interval session was 5 × 4–5 min with 2–3 min rest in between. The use of specific HIT sessions during different phases of the annual cycle is presented in **Figure 4C**.

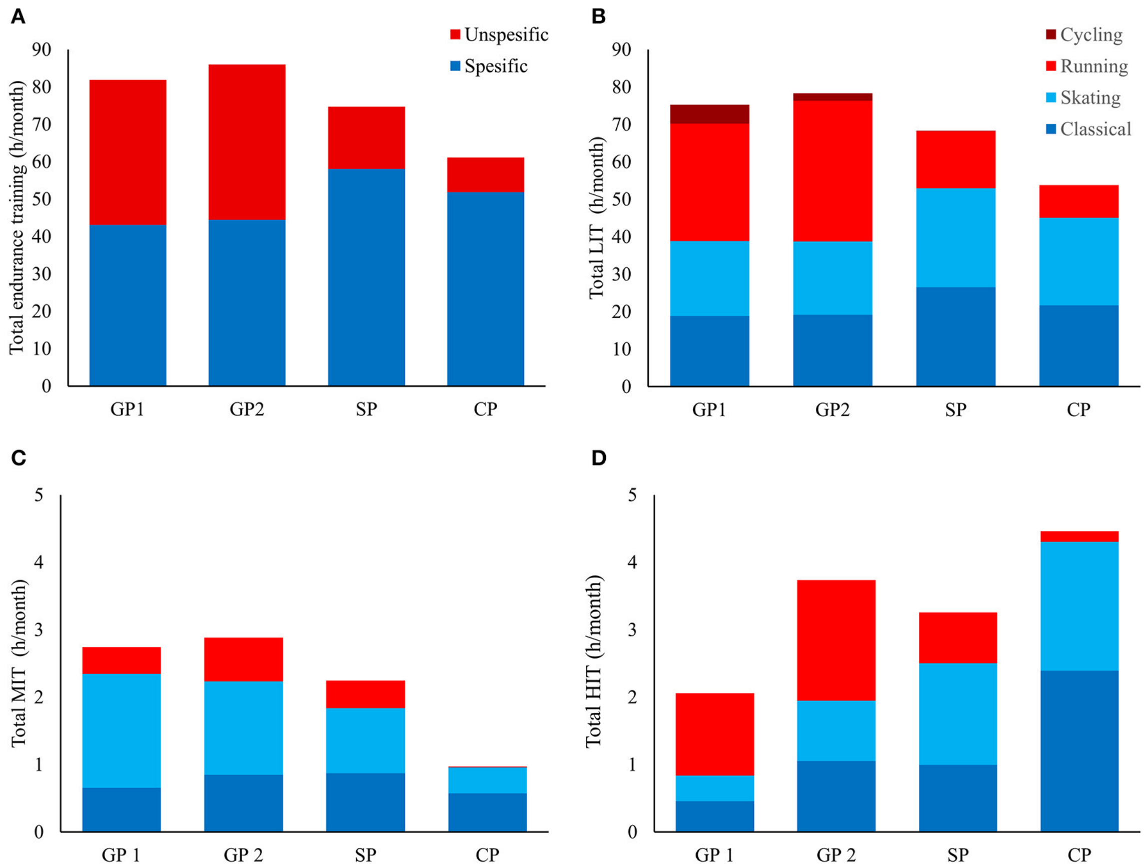

FIGURE 3 | (A–D) Distribution of specific (skiing classical or skating) and non-specific activity forms (running and cycling) presented as total endurance and speed training time **(A)**, low—intensity training time **(B)**, moderate—intensity training time **(C)** and high—intensity training time **(D)** across phases during the successful 2010–2015 period.

TABLE 4 | Weekly training distribution (mean ± SD) across the diffrent periodization phases including the different phases of the altitude camp performed in October and the 6 weeks prior to international championships during the five successfull years from 2010–2015 for the world's most successful female cross-country skier.

	GP1	GP2				SP	CP			
		Overall	Pre altitude	During altitude	After altitude		Overall	Pre-peaking Phase 1	Pre-peaking Phase 2	Peaking phase
TOTAL TRAINING										
Hours	20.9 ± 1.3	21.7 ± 0.6	19.9 ± 1.0	27.6 ± 1.6	18.3 ± 1.5	18.4 ± 0.5	14.7 ± 0.8	15.8 ± 2.2	19.7 ± 2.7	16.2 ± 0.5
Sessions	10.8 ± 0.3	11.1 ± 0.2	10.9 ± 0.4	11.9 ± 0.6	10.3 ± 0.9	11.7 ± 0.5	10.5 ± 0.6	10.8 ± 1.0	11.3 ± 1.5	11.9 ± 0.3
TRAINING FORMS										
Endurance (h)	18.3 ± 0.6	19.4 ± 0.6	16.9 ± 0.4	26.1 ± 1.0	16.2 ± 1.7	16.9 ± 0.4	14.0 ± 0.7	15.2 ± 2.0	17.6 ± 2.1	15.3 ± 0.7
Strength (h)	2.2 ± 0.6	1.9 ± 0.7	2.6 ± 0.6	1.4 ± 0.8	1.8 ± 0.7	1.2 ± 0.3	0.6 ± 0.2	0.5 ± 0.0	1.9 ± 0.9	0.6 ± 0.5
Speed (h)	0.4 ± 0.1	0.4 ± 0.1	0.4 ± 0.2	0.2 ± 0.1	0.3 ± 0.2	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.3 ± 0.1
EXERCISE MODE										
Specific (h)	9.8 ± 0.5	10.0 ± 0.5	7.1 ± 2.3	19.2 ± 4.8	9.2 ± 1.1	13.3 ± 1.2	12.0 ± 0.8	13.8 ± 2.0	15.3 ± 2.1	13.6 ± 0.7
Unspecific (h)	8.8 ± 0.6	9.7 ± 0.4	10.2 ± 2.9	7.1 ± 2.9	7.3 ± 0.9	3.8 ± 0.9	2.1 ± 0.3	1.5 ± 0.6	2.5 ± 0.6	2.0 ± 0.2
SPE/UNSPE (%)	53/47	51/49	41/59	73/27	56/44	78/22	85/15	90/10	86/14	87/13
INTENSITY DISTRIBUTION										
LIT (h)	17.2 ± 0.5	17.9 ± 0.6	15.4 ± 0.5	24.7 ± 1.1	14.8 ± 1.8	15.7 ± 0.4	12.7 ± 0.7	14.0 ± 2.1	16.2 ± 0.9	14.0 ± 1.6
MIT (h)	0.6 ± 0.2	0.7 ± 0.1	0.4 ± 0.4	1.2 ± 0.3	0.7 ± 0.2	0.5 ± 0.1	0.2 ± 0.0	0.3 ± 0.1	0.4 ± 0.3	0.3 ± 0.2
HIT (h)	0.5 ± 0.1	0.8 ± 0.1	1.1 ± 0.2	0.2 ± 0.2	0.7 ± 0.2	0.7 ± 0.1	1.1 ± 0.1	0.9 ± 0.2	1.0 ± 0.1	1.0 ± 0.1
LIT/MIT/HIT (%)	94/3/3	92/4/4	91/2/7	94/5/1	92/4/4	93/3/4	91/1/8	92/2/6	92/2/6	91/2/7
INTENSITY DISTRIBUTION										
LIT (sessions)	7.1 ± 0.3	6.9 ± 0.3	6.1 ± 1.2	8.6 ± 0.8	6.6 ± 0.8	7.8 ± 0.5	7.3 ± 0.5	7.1 ± 0.9	7.1 ± 1.0	8.3 ± 0.5
MIT (sessions)	0.8 ± 0.2	0.9 ± 0.1	0.7 ± 0.8	1.6 ± 0.3	0.9 ± 0.3	0.8 ± 0.2	0.5 ± 0.1	0.8 ± 0.5	0.5 ± 0.4	0.6 ± 0.3
HIT (sessions)	0.9 ± 0.2	1.6 ± 0.1	2.2 ± 0.3	0.3 ± 0.3	1.3 ± 0.3	1.9 ± 0.3	2.1 ± 0.2	2.3 ± 0.3	2.0 ± 0.0	2.3 ± 0.3
LIT/MIT/HIT (%)	80/9/11	74/9/17	68/8/24	82/16/2	76/10/14	74/8/18	74/5/21	71/7/22	74/5/21	74/6/20
CATEGORIZATION OF LIT										
<50 min (sessions)	0.2 ± 0.2	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.9 ± 0.7	2.8 ± 0.5	2.1 ± 0.5	1.1 ± 0.8	3.0 ± 0.4
50–90 min (sessions)	1.0 ± 0.2	1.1 ± 0.3	1.1 ± 1.0	0.5 ± 0.4	1.5 ± 1.1	1.7 ± 0.6	1.3 ± 0.4	1.4 ± 0.8	1.3 ± 0.5	2.4 ± 1.7
90–150 min (sessions)	4.4 ± 0.5	4.0 ± 0.4	4.7 ± 0.8	3.9 ± 0.6	4.8 ± 1.0	3.2 ± 0.2	2.4 ± 0.4	3.0 ± 0.7	3.1 ± 0.8	2.4 ± 0.9
≥150 min (sessions)	1.6 ± 0.5	1.8 ± 0.1	0.5 ± 0.4	4.5 ± 0.7	0.5 ± 0.4	1.0 ± 0.4	0.7 ± 0.2	0.9 ± 0.8	1.8 ± 0.3	1.0 ± 0.7
AVG. SESSION DURATION										
LIT (h)	2.0 ± 0.1	2.1 ± 0.1	1.8 ± 0.1	2.6 ± 0.1	1.8 ± 0.1	1.5 ± 0.1	1.3 ± 0.1	1.4 ± 0.1	1.7 ± 0.1	1.3 ± 0.2
MIT (h)	0.8 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	0.8 ± 0.1	0.7 ± 0.0	0.7 ± 0.1	0.5 ± 0.1	0.2 ± 0.1	0.4 ± 0.3	0.3 ± 0.2
HIT (h)	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.1	0.7 ± 0.0	0.5 ± 0.0	0.4 ± 0.0	0.5 ± 0.1	0.4 ± 0.1	0.5 ± 0.1	0.5 ± 0.0
COMPETITIONS										
Hours	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.4 ± 0.1	0.7 ± 0.1	0.6 ± 0.3	0.5 ± 0.3	0.3 ± 0.1
Number	0.2 ± 0.1	0.3 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.1 ± 0.2	1.5 ± 0.2	1.6 ± 0.5	1.0 ± 0.6	0.9 ± 0.3

GP1, general preparation period 1; GP2, General preparation period 2; SP, Specific preparation period; CP, Competitions phase; SPE, Specific exercise mode; UNSPE, Unspecific exercise mode; LIT, Low intensity training; MIT, moderate intensity training; HIT, High intensity training.

Strength and Speed Training

An important change during the five investigated years was an increase in annual strength training time from ∼51 h (43% core stabilization and 57% heavy strength training) during the first 2 years (30–32 years old), to ∼90 h (50% core stabilization and 50% heavy strength training) in the following 3 years. This increase was due to both an increased number (55–75 sessions) and duration (0.9–1.2 h) of sessions. The amount of strength training increased from 6.0 to 10.9 h/month in GP, from 2.6 to 4.2 h/month in SP and from 1.7 to 3.0 h/month in CP. The proportion of heavy versus core/stabilization training across phases was relatively similar during all 5 years, with the amount of heavy strength training increasing from GP (∼50%), to SP (∼60%) and further to CP (∼65%).

A typical strength session consisted of 30–45 min of core/stabilization exercises followed by 30–45 min of heavy strength training. The core stabilization portion included various exercises targeting muscles involved in the force transfer during specific ski movements and exercises aiming to stabilize and move these segments functionally while skiing. Heavy strength sessions consisted of one or two leg exercises (e.g., squats) and three to four upper-body exercises (e.g., seated pull-down, standing double poling, pull-ups, lying bench-pull, and pullover).

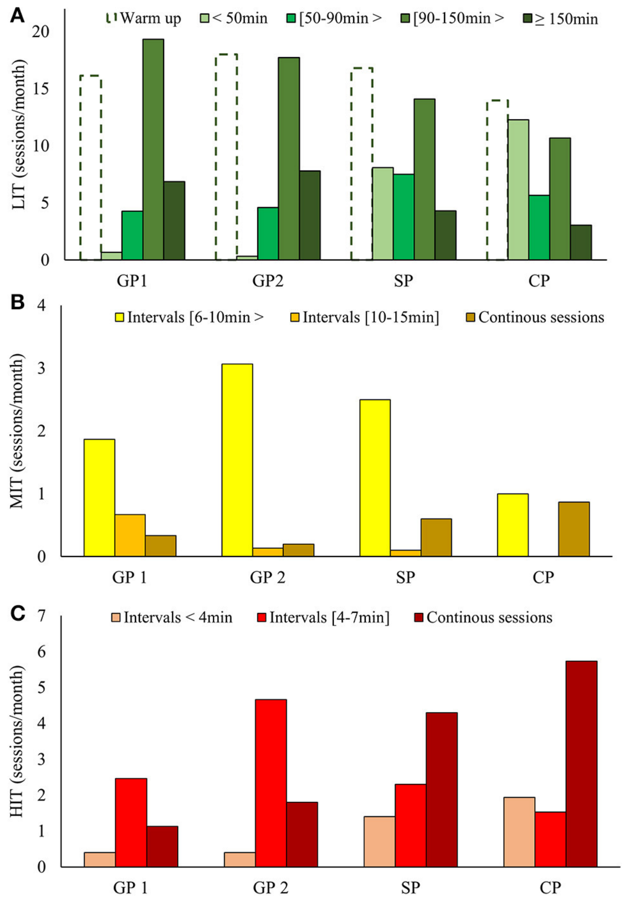

FIGURE 4 | (A–C) Distribution of low- **(A),** moderate- **(B)** and high-intensity **(C)** sessions, categorized after duration and/or organization, across phases during the five most successful years (2010–2015).

Annually, 14 ± 2 h of speed training, including 11.1 h ski-specific exercises and 2.5 h of jumps/plyometrics, was performed. The amount of speed training decreased from GP (1.7 h/month) to SP (0.9 h/month) and CP (0.5 h/month). Speed training was included 64 ± 9 times/year and typically performed as 6–10 × 10–20 s sprints or 5–8 series of 10–15 plyometric jumps using ski specific movements integrated into LIT sessions of 90–120 minutes or performed before strength sessions.

Exercise Modes

63 ± 3% (545 ± 18 h) of the yearly endurance and sprint training was performed as sport-specific exercise modes (i.e., skating and classical on skis or roller skis), with the remaining 37 ± 2% (318 ± 18 h) performed as non-specific activity forms (34% running and 3% cycling). The proportion of specific activity forms increased from GP (52%) to SP (78%) and further to CP (85%). Specific training time also increased from GP (44 h/month) to SP (58 h/month), but then decreased slightly to CP (52 h/month). Sport-specific training accounted for 62, 83, and 72% of the annual LIT, MIT, and HIT volume, respectively. **Figures 3A–D** illustrate the distribution of activity forms across the different intensities and training phases. The distribution of training in the classic and skating techniques were approximately equal in total training time (48 and 52%), LIT (49 and 51%), and HIT (49 and 51%), while the proportion of skating was substantially higher during MIT (61%).

Altitude Training

Total annual days spent at altitude was 61 ± 9, which were mainly distributed across five altitude camps (12–14 days June/July, 12–14 days August/September, 14–16 days October/November, 10–14 days in December and 10–12 days January/February). Total training volume at altitude ranged from 170 to 230 h, accounting for 18–25% of the total annual training volume. The average weekly training volume decreased from altitude camps performed in GP (∼26 h) to SP (∼22 h) and further to CP (∼20 h).

Training during the 2 weeks before, 2 weeks during and the 2 weeks after the altitude camp in October/November are presented in **Table 4** and **Figure 5A**. Total training volume was ∼35% higher during altitude than the phases before and after. The increased training volume occurred due to an increased number of LIT session's ≥2.5 h, whereas strength training time was lower during altitude compared to the phases before and after. The amount of training in specific modes increased markedly at altitude, while the total volume of MIT and HIT remained stable (∼1.5 h/week) across all three phases. However, the MIT/HIT distribution changed from containing more HIT before altitude (0.4 h MIT vs. 1.1 h HIT), but more MIT during altitude (1.2 h MIT vs. 0.2 h HIT) and equal amounts of MIT and HIT after altitude training (0.7 h MIT vs. 0.7 h HIT).

Tapering toward International Championships

The distribution of training during the final 6 weeks prior to gold medal performance is presented in **Table 4** and **Figure 5B**. Here, training volume increased by 25% from pre-peaking phase 1 (day 42–29) to pre-peaking phase 2 (day 28–15), due to increased amount of long duration LIT sessions and strength training. The training volume was then reduced by 18% to the peaking phase (day 14–1), which included a modest reduction in volume (6%) during the first week (day 14–8) and a larger reduction (30%) in the final week (day 7–1). The training volumes during the three consecutive peaking phases were 73, 91, and 75 % of the average GP2 training volume, respectively, while the number of sessions was stable across all phases (∼11 sessions/week).

The amount of MIT+HIT volume remained relatively stable across all peaking phases (∼1.3 h/week). Week-by-week analyses showed a progressive increase in the proportion of HIT vs. MIT during the final 3 weeks before the championship start. A detailed description of the specific sessions performed during the final 14 days before the 2014 Olympic Games is presented in **Table 5**.

DISCUSSION

The present study investigated the training routines during the best-performing period of the most successful female XC skier of all time, analyzed in the context of her longitudinal training patterns. Following a 12-year progressive, non-linear increase in training load, the annual training volume during these 5 years

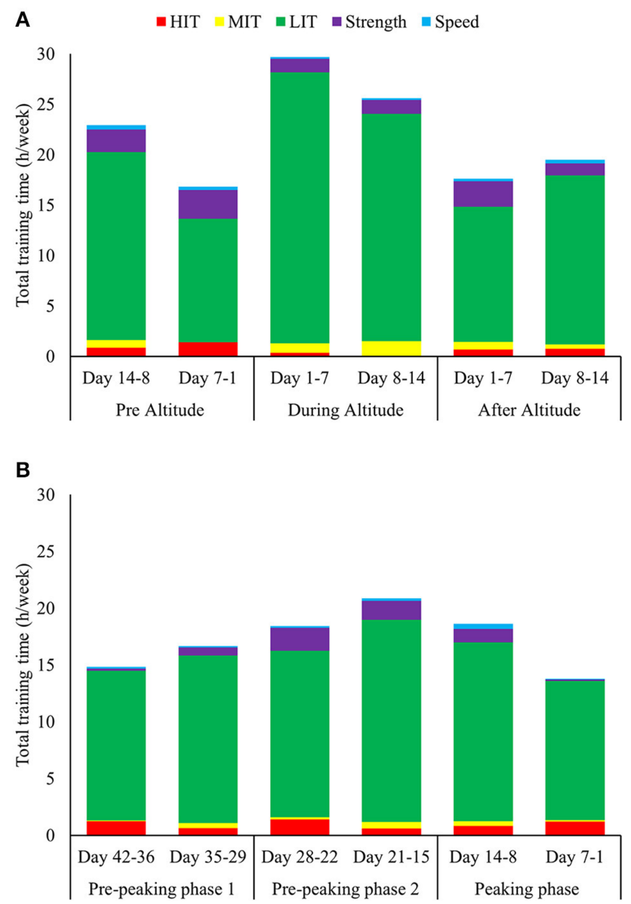

FIGURE 5 | (A,B) Total weekly training distributions of **(A)** the 2 weeks before-, 2 weeks during- and 2 weeks after the annual altitude camp in October, and **(B)** the final 6 weeks before the four international championships performed in February during the period from 2010–2015, distributed into endurance training (low-, moderate-, and high-intensity), strength- and speed training.

was ∼940 h, consisting of 91% endurance-, 8% strength-, and 1% speed training. Endurance training was gradually more polarized, due to reduced LIT and increased HIT, from GP to CP. 18–25% of the annual training time was done at altitude, performed with relatively short training camps (≤16 days) where HIT training is reduced and LIT training increased compared to sea-level training. Training before international championships included a 2-week increase in LIT and strength volume followed by gradual reduction in total training volume and increased HIT during the final week.

Longitudinal and General Training Characteristics

In this study, in which 17 years of training were analyzed, our participant had a 12-year progressive, non-linear increase in training load from the age of 20 until the successful 5-year period analyzed in detail, where annual training volume was ∼940 h, distributed across ∼540 sessions. The overall progression in training mainly included an increase in LIT, although in a 6-year period she also increased the amount of HIT due to extensive blocks of HIT training during GP. The participant was already at a high international level and achieved her first international gold medal at 23 years old, with training volumes slightly in excess of 700 h. However, before the age of 25 she was not stable at the top level in distance races and mainly performed at a world-class level in sprint skiing; after which she performed equally well in all disciplines and techniques. While these data highlight the importance of a high training volume to achieve a top international level in XC-skiing (Tonnessen et al., 2014; Sandbakk et al., 2016; Sandbakk and Holmberg, 2017), they also indicate that a progressive increase in training load is beneficial.

Throughout the 12 initial years with increases in training load, our participant had two major changes in "training philosophy," in which rapid performance improvements also occurred. The first of these periods was in an early stage of her senior career, where extensive blocks of HIT were included. This led to rapid performance improvements that stagnated after a few years, during which the progression in training load and/or variation in stimulus were limited. The next major performance improvement coincided with a change to a more even distribution of training volume/intensity, a reduction in the amount of HIT, and the implementation of relatively large amounts of LIT. This occurred directly before entering the successful 5-year period analyzed here. In this period, both physiological values and performance improved over the first year before remaining at a stable high level. The annual training volume of >910 h consisted of ∼850 h endurance training distributed as 92% LIT, 3% MIT, and 5% HIT when using the modified session-goal approach to quantify training. When quantified by the number of sessions in each zone, ∼475 endurance sessions were distributed into 76% LIT, 7% MIT, and 17% HIT. While these amounts of HIT and MIT are similar to what was previously reported in world-class XC skiers (Sandbakk et al., 2011b, 2016; Tonnessen et al., 2014), the volume of LIT is remarkably high. This was combined with relatively high amounts of strength training and regular speed training, which may have been beneficial for maintaining muscle mass and sprint ability. A further progression in stimuli was achieved through inclusion of more strength training halfway through the 5-year period, while the amount of endurance training remained relatively stable. One unique feature of our participant is that she combines a high aerobic capacity with greater muscle mass than normally reported among female XC skiers (Hegge et al., 2016), particularly in the upper-body where women typically have the largest difference in body composition and performance compared to men (Sandbakk et al., 2017).

In XC skiing, not just exercise volume, frequency, and intensity are of importance. Through the 17-year period, ∼60% of annual endurance and sprint training hours were ski specific (skiing on snow or roller skis), while the rest was primarily running. This alternation between exercise modes, loading the whole body, upper body, and the legs to a different extent, is unique for XC-skiing compared to other endurance sports. The variation between employment of these training modes permits high training loads during GP, while the total training load is reduced when less variation and increased sport-specific training

TABLE 5 | Detailed description of the training performed during the final 14 days before the 2014 Olympic Games in Sochi, including information about the commonalities during the same period before the World Championships in 2011, 2013, and 2015 for the world's most successful female cross-country skier.

	Training content	Commonalities 2011, 2013, 2014, and 2015
14	AM: 2.5 h LIT, ski skating on varying terrain PM: Warm-up + 30 min strength training#	**Day 14–8 before first championship event:** • Second part of 10–12 days altitude camp at 1,800 m.a.s.l (i.e., the entire altitude camp was 8–20 days before the first competition) • Training volume 17–20 h • 2–3 LIT sessions >2.5 h • 2 MIT/HIT sessions performed at 1,000 m.a.s.l • 1–2 strength sessions • 2–4 LIT sessions whit integrated sprints • 1 rest day
13	Rest day	
12	AM: 2.5 h LIT, classical skiing on varying terrain PM: 1.3 h LIT, ski skating on varied terrain, including sprints	
11	AM: 5 × 7-min MIT*, ski skating on varied terrain PM: 1.3 h LIT, classical skiing on varied terrain, including sprints	
10	AM: 2.7 h LIT, classical skiing on varied terrain PM: Warm-up + 30 min strength training#	
9	AM: 2.3 h LIT, ski skating on varied terrain, including sprints PM: Rest	
8	AM: 6 min MIT + 5-km HIT*, classical skiing varying terrain PM: 0.5 h LIT, running	
7	AM: 1.3 h LIT, classical skiing on varied terrain, including sprints PM: 0.5 h LIT, running	**Day 7–1 before first championship event:** • Training at championship elevation • Total training volume of 13–16 h • 3–4 HIT/MIT sessions • Frequent medium and short duration LIT sessions • Timing of sessions ▪ Day 6–4: 1–3 competitions ▪ Day 3: Easy day with LIT ▪ Day 2: HIT session or easy training with LIT ▪ Day 1: Easy training or short duration MIT session
6	MO: 0.5 h LIT, running AM: 10-km classic competition* PM: 0.5 h LIT, running	
5	AM: Sprint skating competition* PM: 0.5 h LIT, running	
4	Rest day with traveling	
3	AM: 1.3 h LIT, ski skating on varied terrain PM: 1.5 h LIT, classical skiing on varying terrain	
2	AM: 30 min HIT*, duathlon ski classical and skating varying terrain PM: 0.5 LIT, running	
1	AM: 1.3 h LIT, classical skiing on varying terrain PM: 0.5 h LIT, running	
0	Gold medal, skiathlon Olympic Winter Games Sochi 2014	

LIT, low-intensity training: heart rate < 87% max; MIT, moderate-intensity training: heart rate 87–92% max; HIT, high-intensity training: heart rate > 92% max.
**MIT and HIT sessions normally included 30–45 min of LIT as warm up and 15–30 min LIT as cool-down.*
#Strength training sessions normally included 30–45 min of LIT as warm u.

is used toward CP. However, variations between exercise modes were also employed on the micro periodization level; e.g., by performing heavy strength training of the upper body in the morning session followed by lower body endurance training (e.g., running) in the afternoon. This way of loading the upper and lower body may not only increase the tolerable training load, but could also reduce negative cross-over adaptation effects from concurrent strength and endurance training. In our case, the participant confirmed during interviews that she was conscious about the use of terrain, e.g., by combining uphill sessions where the legs are mainly employed, with sessions primarily loading the upper body by using the double poling technique on the same day. This is likely an important factor contributing to the combination of high endurance capacity and a relatively large muscle mass obtained by XC skiers.

Following a gradual increase in aerobic capacity, the participant's average VO_{2max} was ∼68 (ml·kg $^{-1}$·min^{-1}) during her five most successful years. This is at the same level reported in female champions in running and orienteering (Jones, 2006; Tonnessen et al., 2015b). Her AT increased correspondingly, and both the participant and her coaches highlighted her gradually improved ability to train with relatively high speed and a high technical quality also during LIT and MIT sessions in all exercise modes. This is supported by her lactate profiles, where her speed at various submaximal lactate levels gradually increased throughout her career. Similar results were shown in the female marathon world record holder (Jones, 2006) and a world-class rower (Bourgois et al., 2014). This is most likely a result of her long-term progressive increase in endurance training load, leading to enhanced peak oxygen uptake, fat utilization and improved efficiency in all exercise modes. In this context, it is also important to note that the body mass of the participant was very stable throughout her senior career, and measurements of body composition during the five successful years showed that both her fat percentage and bone mineral density were within healthy values. We suggest that this is an important reason for her continuity in training during the 17 years with high loads of endurance training.

Overall, our data indicate that a progressive increase in training load until the age of 30 may be necessary in order to optimize the full potential of a top-level XC skier. We hypothesize that this allowed our champion XC skier to tolerate and respond positively to the high training volumes utilized in the 5-year period analyzed, where she used a polarized training pattern with a large amount of LIT.

Training Characteristics during Five Successful Years

Annual Periodization of Training

The total number of LIT sessions remained stable across phases throughout the training year, while total LIT-time was gradually reduced from GP to CP. The amount of MIT, speed, and strength training also decreased from GP to CP, while HIT showed the opposite pattern, which altogether induced a gradually more polarized training pattern toward CP. The transition from a more "pyramidal" to a more polarized endurance training pattern was previously shown in successful athletes (Stoggl and Sperlich, 2015). However, the large amounts of speed and strength training during GP might be an important addition to concurrently develop endurance and strength capacities during the preparation period, whereas the subsequently more polarized pattern may facilitate the ability to utilize these capacities at competition-specific intensities.

Simultaneously, the amount of specific training increased from 50% during GP to 85% in CP. This is in line with previous studies of XC skiers and probably functions as an important substitute for reduced volume during CP (Tonnessen et al., 2014). While the sport-specific proportion of LIT and HIT increased markedly from GP to CP, the amount of specific MIT was >80% during all phases. In addition, the MIT sessions were performed at relative high heart rates (87–92% of HR_{max}), which is higher than normally reported in elite athletes, although RPE ratings and lactate values were in the normal range for such sessions. The participant confirmed that she was able to perform MIT sessions at this level, which allowed her to accumulate and tolerate much more time at >90% of HR_{max} than most of her peers. Such training has previously been reported to be highly effective for endurance adaptations and performance in well trained elite athletes (Stepto et al., 1999; Sandbakk et al., 2013).

The accumulated LIT-time during GP was very high (76 h/month) and reduced in CP (55 h/month). While the number of LIT sessions remained stable across phases (∼32 sessions/month), the amount of LIT sessions ≥90 min decreased from GP (25 sessions/month) to CP (14 sessions/month). Another pronounced change between phases was the increase of LIT sessions <50 min from GP (∼0 sessions/month) to CP (∼14 sessions/month). This methodological approach is novel, and clearly shows how LIT sessions of different duration are distributed differently throughout the year. The effect of duration versus frequency of LIT sessions has not yet been examined, although up to 90% of the total training among endurance athletes is LIT. Interestingly, 21% (167 h) of the annual LIT volume was warm up or cool down in connection with MIT, HIT, or strength sessions. This part of LIT probably functions as an important contributor to the long-term development by enhancing the total training volume.

While the majority of MIT and HIT sessions were organized as intervals during GP, an increase in continuous MIT and HIT sessions was observed as the CP approached. Both exercise mode, organization of HIT, and use of terrain got more specific closer to CP. The fact that 42% of annual HIT time was competitions emphasizes the importance of specific training to achieve success in XC skiing. The participant also confirmed that competitions were an important part of her training, particularly during her tapering phase. The organization of endurance sessions changed from longer to gradually prioritizing shorter LIT sessions, while MIT and HIT sessions became more competition-specific.

Altitude Training

18–25% of annual training volume was performed during relatively short (10–16 days) altitude camps, living at 1,800–2,000 m.a.s.l and training at 1,000–3,000 m.a.s.l., with a clear reduction in HIT but an increased volume of LIT compared to sea-level training. This altitude exposure is significantly shorter than the 4 weeks recommended to fully stimulate erythropoiesis. However, comparable duration of camps is reported to have beneficial effects on work economy, muscle buffering capacity, and ventilatory factors (Millet et al., 2010). Furthermore, the long-term effect of repeated short-duration altitude exposure over several years is currently unknown.

The participant experienced marked progress after altitude training, although it is not known to what extent altitude-facilitated effects and/or the periodization of training occurring in connection with altitude camps influence the experienced progress. Before altitude, training changed toward a more polarized pattern, including lower total volume and more HIT and strength training. During altitude, HIT was reduced and training shifted to a more pyramidal intensity distribution, with more LIT sessions ≥2.5 h and increased amounts of MIT. Training after altitude consisted of some easy days with reduced volume and no MIT or HIT during the first 4 days after altitude exposure, followed by increased intensity in training. The participant also highlighted the opportunity to ski on snow, more time to rest, and an increased focus on recovery as possible factors contributing to the positive effect of altitude camps.

Tapering toward International Championships

The tapering phase prior to international championships included a phase with frequent competitions, followed by elevated training volume including more LIT and strength at altitude. Thereafter, our participant reduced her training volume and increased the amount of HIT during the final week before championships. However, the reduction in training volume during the final 2 weeks (18%) was much lower than recommendations in the literature (Bosquet et al., 2007). The same observation was made by Tonnessen et al. (2014), where the authors speculated that this might be optimal in sports with a dense competition schedule. As such, top athletes in XC skiing appear to reduce their training volume less than that recommended by the current literature. Maintenance of training volume until the final week before the first championship event could also be important in order to maintain performance level over 5–6 competitions during a championship lasting 9–15 days.

Our participant integrated the competition schedule into the tapering strategy and had a relatively similar timing of the final competitions in the peaking phase during all 5 years. Specifically, a period with frequent competitions, allowing less training hours, is followed by a competition break, prioritizing altitude training with more MIT, long duration LIT sessions and strength training. Thereafter, three HIT sessions were performed during the final 7 days, which include competitions at day 6–4 before the championship's start. However, since this analysis is based on the training conducted prior to the first competition in each championship, it is not certain that this was the day with the best performance (although gold medals were won already at the first competition).

CONCLUSION

Our study supports previous findings highlighting the importance of a high training volume, using a polarized training pattern with a large amount of LIT to reach world-class level in XC skiing. This study provides unique data on the world's most successful XC skier's long-term training process, including novel information about the physiological development and the distribution of and interplay between sessions of different training forms, intensities, and exercise modes throughout the annual season. By using a single-case approach, where quantitative data were supported by qualitative interviews, we were able to present the sophisticated training of a world-class athlete from a macro- to a micro-level, allowing the generation of new hypotheses that can be tested in future research with larger samples.

AUTHOR CONTRIBUTIONS

GS, ET, and ØS designed the study; GS performed data collection; GS, ET, and ØS performed data and statistical- analysis; GS, ET, and ØS contributed to interpretation of the results; GS and ØS wrote the draft manuscript; GS, ET, and ØS contributed to the final manuscript.

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frontiers in Physiology

REVIEW
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Massage Alleviates Delayed Onset Muscle Soreness after Strenuous Exercise: A Systematic Review and Meta-Analysis

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Purpose: The purpose of this systematic review and meta-analysis was to evaluate the effects of massage on alleviating delayed onset of muscle soreness (DOMS) and muscle performance after strenuous exercise.

Method: Seven databases consisting of PubMed, Embase, EBSCO, Cochrane Library, Web of Science, CNKI and Wanfang were searched up to December 2016. Randomized controlled trials (RCTs) were eligible and the outcomes of muscle soreness, performance (including muscle maximal isometric force (MIF) and peak torque) and creatine kinase (CK) were used to assess the effectiveness of massage intervention on DOMS.

Results: Eleven articles with a total of 23 data points (involving 504 participants) satisfied the inclusion criteria and were pooled in the meta-analysis. The findings demonstrated that muscle soreness rating decreased significantly when the participants received massage intervention compared with no intervention at 24 h (SMD: –0.61, 95% CI: –1.17 to –0.05, $P = 0.03$), 48 h (SMD: –1.51, 95% CI: –2.24 to –0.77, $P < 0.001$), 72 h (SMD: –1.46, 95% CI: –2.59 to –0.33, $P = 0.01$) and in total (SMD: –1.16, 95% CI: –1.60 to –0.72, $P < 0.001$) after intense exercise. Additionally, massage therapy improved MIF (SMD: 0.56, 95% CI: 0.21–0.90, $P = 0.002$) and peak torque (SMD: 0.38, 95% CI: 0.04–0.71, $P = 0.03$) as total effects. Furthermore, the serum CK level was reduced when participants received massage intervention (SMD: –0.64, 95% CI: –1.04 to –0.25, $P = 0.001$).

Conclusion: The current evidence suggests that massage therapy after strenuous exercise could be effective for alleviating DOMS and improving muscle performance.

Keywords: massage, physiotherapy, exercise, delayed onset muscle soreness (DOMS), systematic review, meta-analysis

Systematic Review Registration: PROSPERO registration number: CRD42016053118.

INTRODUCTION

It is well established that keeping an active lifestyle through exercise benefits human health, especially reducing the risk of obesity and cardiovascular disease. However, exhaustive or unaccustomed exercise (particularly involving eccentric contractions) frequently result in temporary muscle damage, leading to delayed onset muscle soreness (DOMS) (Bleakley et al., 2012).

DOMS commonly occurs within the first 24 h after exhaustive or intense exercise, reaching a peak between 24 and 72 h (Howatson and van Someren, 2008). It is often accompanied by muscle swelling and reduction in muscle performance (Kargarfard et al., 2016; De Marchi et al., 2017), as well as a decrease in range of motion (Cheung et al., 2003; Lavender and Nosaka, 2006). Although the exact mechanism of DOMS remains unclear, the most accepted theory suggests primary mechanical damage induced by exercise, followed by inflammation attributing to the symptoms of DOMS. This is verified by microscopic analysis showing disruption of muscle fibers. In addition, there is also an increase of intracellular enzymes such as creatine kinase (CK) and inflammatory markers in blood (Peake et al., 2005a,b; Chatzinikolaou et al., 2010).

In an attempt to prevent or alleviate the symptoms of DOMS, a number of conventional physiotherapeutic strategies were used such as massage, cold-water immersion, whole body vibration, compression garments, and stretching (Weerapong et al., 2005; Howatson et al., 2009; Bleakley et al., 2012; Costello et al., 2012; Hill et al., 2014). Therapeutic massage has been used for body health for thousands of years worldwide. As a physiotherapeutic intervention, massage treatment is widely used to alleviate clinical symptoms of DOMS, and to benefit the athlete's recovery after exercise in preparation for the next event (Poppendieck et al., 2016). The potential effectiveness of massage therapy is proposed to increase skin and muscle temperature, blood and lymphatic flow, and parasympathetic activity. Subsequently, the effects include then relief of muscle tension and stiffness, reduction of muscle soreness, and increased joint range of motion (Weerapong et al., 2005). In addition, changes in the Hoffman reflex after massage also contributes to the reduction of muscle pain (Morelli et al., 1999). Moreover, the psychophysiological response to massage, including relaxation, leads to mood enhancement and fatigue reduction (Hemmings et al., 2000).

Previous systematic reviews have shown benefits from massage for symptoms of DOMS after intense exercise. However, little support for the use of massage was observed to enhance muscle performance (Ernst, 1998; Best et al., 2008), including peak torque and maximal isometric force, factors that are important for sporting events. It seems that the psychological effect is larger than the physiological effect. Torres et al. demonstrated that massage could reduce muscle soreness and increase muscle recovery 24 h post-exercise based on a meta-analysis, but there were only few trials pooled in the meta-analysis (3 trials) (Torres et al., 2012). Currently, the evidence of the effects of massage intervention on DOMS still limited. Therefore, the purpose of this study was to evaluate the effectiveness of massage on DOMS and muscle performance after strenuous exercise.

METHOD

Search Strategy

Relevant research articles from January 1980 to December 2016 were collected with keywords such as "exercise," "massage," "delayed onset muscle soreness," and "random" from the following databases: PubMed, Embase, EBSCO, Cochrane Library, Web of Science, China Knowledge Resource Integrated Database (CNKI) and Wanfang Database. The search was imposed with the limitation of randomized controlled trials (RCTs), and without language or status limitations. Supplementary Data (S1) details all of the search strategies used in this study. The protocol was registered on the international prospective register of systematic reviews PROSPERO (http://www.crd.york.ac.uk/PROSPERO), registration number: CRD42016053118.

Inclusion Criteria

Trials were included when they met the inclusion criteria as follows: (a) only the trials designed as RCTs were covered, (b) participants were human with no muscle or bone diseases, (3) the trials compared post-exercise massage intervention with the control group receiving usual care, or no intervention, (4) outcomes included the primary outcome of muscle pain or soreness rating, the secondary outcome: muscle strength (i.e., maximal isometric force (MIF) and peak torque), and the level of serum CK. Mean and standard deviation (SD) were reported in the trials.

Exclusion Criteria

Trials were excluded when they met the exclusion criteria as the following: (a) the articles were conference posters, abstracts, or case reports; (b) mean and SD could not be obtained from the articles or authors.

Studies Selection

Two reviewers (Guo JM and Li LJ) independently reviewed the titles or abstracts of all studies, and the full contents of the relevant studies were checked carefully to evaluate whether the study could be included. Any disagreements were resolved by discussion or consultation with a third author (Chen X) if necessary.

Quality Assessment

The Cochrane Collaboration tool was used to evaluate the risk of bias of the included trials (Higgins et al., 2011). Two reviewers (Guo JM and Li LJ) independently evaluated seven domain biases as follows: random sequence generation (selection bias), allocation concealment (selection bias), blinding of participants and personnel (performance bias), blinding of outcome assessment (detection bias), incomplete outcome data (attrition bias), and selective reporting (reporting bias). Three grades of high, low, or unclear bias were labeled for every study included. Disagreements were resolved by discussion or consulting with a third independent reviewer (Chen X) if necessary.

Data Extraction

The two reviewers independently extracted the data from every included eligible trial as the following: study characteristics (i.e., author and year), participant characteristics (i.e., age and number of participants), description of interventions, study period, outcomes, and time points. Any disagreements were settled by discussion to reach unanimity, and the authors of the trials were contacted directly to acquire original studies and data if necessary.

Statistical Analysis

The Review Manager software (RevMan 5.3; Cochrane Collaboration) was used to perform the meta-analysis. Heterogeneity among studies was evaluated by I^2 statistic as follows: low heterogeneity was assumed when $I^2 < 25\%$; moderate heterogeneity when $I^2 < 75\%$ and $>25\%$; high heterogeneity when $I^2 \geq 75\%$ (Higgins et al., 2003). Meta-analysis was used to combine two or more outcomes from the studies by random-effects or by a fixed-effect model. The fixed-effect model was used when $I^2 < 25\%$ and the random-effects model was used if $I^2 > 25\%$. As the trials used different scales for muscle soreness rating assessment, we used standardized mean difference (SMD) to analyze the effects. If $P < 0.05$, it was considered to be a significant difference. Subgroups were used to analyze the effectiveness of massage at different time points after strenuous exercise. The possible publication bias was evaluated by Funnel plot asymmetry if more than nine trials were included. Sensitivity analysis was used when $I^2 > 50\%$, removing each trial one by one to evaluate the stability of the results.

If the included articles did not report mean and SD, we would contact the authors to ask for data, and the articles would be excluded if there was no reply. When the articles showed the data as median and interquartile range (IQR), the mean would be equivalent to the median, and the SD would be calculated as $SD = \text{IQR}/1.35$ (Wang et al., 2016). If the articles reported the data in terms of mean and standard error (SE), the SD would be calculated as $\text{SD} = \text{SE} \times \sqrt{n}$ (n meaning sample size) (Higgins and Green, 2011; Higgins et al., 2011).

RESULTS

Search Results

From our initial search, 882 records were obtained. After reviewing the information on the articles' title and abstract, 70 potentially eligible articles were identified. After reviewing the full content of the studies, 11 articles with 23 data points (504 participants) satisfied the inclusion criteria and were pooled in this meta-analysis (Weber et al., 1994; Lightfoot et al., 1997; Hilbert et al., 2003; Mancinelli et al., 2006; Yang, 2007; Frey Law et al., 2008; Xiong et al., 2009; Hu et al., 2010; Andersen et al., 2013; Imtiyaz et al., 2014; Kargarfard et al., 2016). The details of the process of identifying articles from initially searching to inclusion are shown in **Figure 1**.

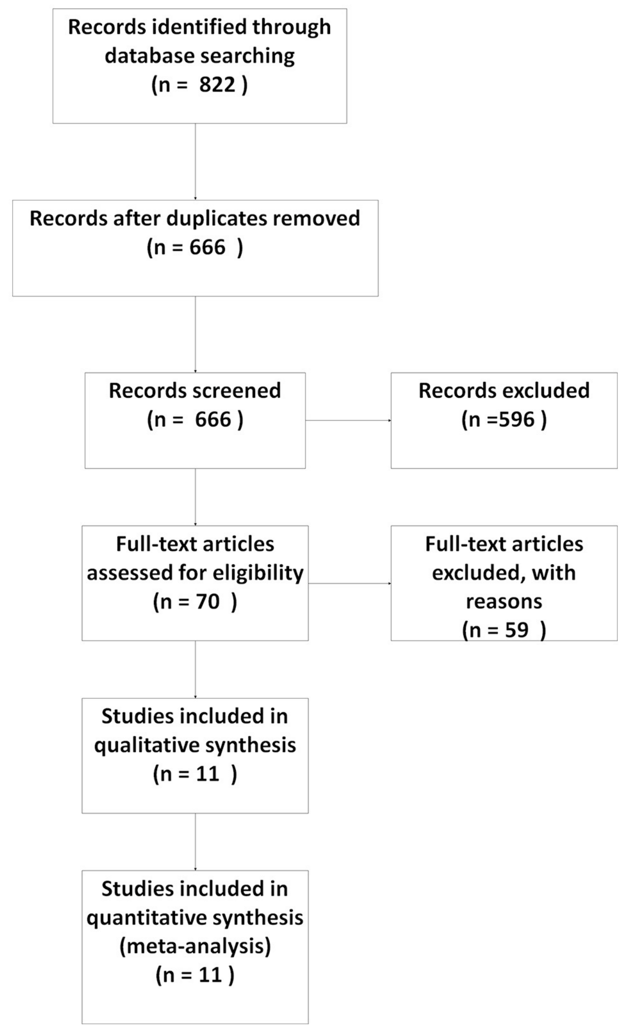

FIGURE 1 | Flow diagram of the study selection.

Description of Included Studies

The characteristics of the included articles were summarized in **Table 1**. Eleven articles were included in this meta-analysis. The distribution of publication countries was as follows: the United States ($n = 5$, 45.5%), the People's Republic of China ($n = 3$, 27.2%), Canada ($n = 1$, 9.1%), India ($n = 1$, 9.1%) and Iran ($n = 1$, 9.1%). Eight articles were published in English, and three in Chinese.

Massage Therapy

Most (eight articles) of the trials used western massage techniques or Swedish massage techniques including effleurage and petrissage. Effleurage is a succession of light and stroking massage, and petrissage is deep-tissue kneading of the muscles. Three articles performed traditional Chinese massage including pushing, swing, grasping, vibrating and plucking. According to the size of the muscle area, the massage intervention duration ranged from 6 to 30 min, but the duration per area approximately

TABLE 1 | Characteristics of included studies.

No	Article, year	Country/ Region	Subjects' characteristic, sample size	Induce DOMS	Intervention	Duration	Outcomes	Time point
1	Weber et al., 1994	USA	20 healthy female untrained volunteers (G1 = 10, G2 = 10). Mean age(SD): G1 = 22.3(4) years, G2 = 25.9(4.5) years	Performed eccentric exercise of nondominant elbow flexion until fatigued	G1: no intervention, G2:massage, light effleurage for 2 min, petrissage for 5 min, effleurage for 1 min.	8 min	Muscle soreness rating, maximal isometric force, peak torque at 60°/s	0, 24, 48 h after DOMS induced exercise
2	Lightfoot et al., 1997	USA	21 normally active college-age volunteers [G1 = 11 (3 men and 8 women), G2 = 10 (6 men and 4 women)]. Mean age(SD): G1 = 23.9(6.4) years, G2 = 26.9(5.6) years	4 sets of 15 repetitions of eccentric exercise (heel-drop) to induce calf muscle DOMS	G1: no intervention, G2: 10 min of petrissage on calf muscle immediately after eccentric exercise, and again at 24 h post-exercise.	10 min twice	Muscle soreness rating, creatine kinase level	0, 24, 48 h after DOMS induced exercise
3	Hilbert et al., 2003	USA	18 male and female volunteers (G1 = 9, G2 = 9).mean age (SD) for all the subjects is 20.4 (1.0) years	6 sets of 10 maximal eccentric contractions with hamstring (1 min of rest between sets), followed by 5 more maximal eccentric contractions.	G1:rest for 20 min while listening to the same audiotape heard by the massage group on placebo lotion. G2:20 min of massage classical Swedish techniques	20 min	Muscle soreness rating, peak eccentric torque	0, 2, 6, 24, 48 h after DOMS induced exercise
4	Mancinelli et al., 2006	USA	22 female basketball and volleyball players. G1 = 11, G2 = 11. Mean age (SD) for all subjects is 20(0.93) years	Intense strength training and drills	G1: no intervention. G2: Western massage techniques of effleurage, petrissage and vibration were used for 17 min on 48 h after DOMS induced training.	17 min	Muscle soreness rating (VAS and PPT)	0 h after treatment (48 h after DOMS induced training)
5	Yang, 2007	China	16 male trained athletic volunteers (G1 = 8, G2 = 8), mean age (SD) for all subjects is 19.2(0.96) years	10 sets of 30 m leapfrog with 1–2 min rest between sets.	G1: no intervention. G2: Chinese traditional massage (including pushing, grasping, vibrating, and plucking) for 15 min.	15 min	Muscle soreness rating, creatine kinase level	0, 24 h after DOMS induced exercise
6	Frey Law et al., 2008	USA	27 healthy individuals participanted in this study as volunteers, G1 = 11, G2 = 16.mean age (SD) for all subjects is 23.3 (3.5) years, range of 19–41 years	3 sets of eccentric wrist extensor contractions using a 10 lb hand weight with 1–2 min between sets.	G1: had a thin layer of massage cream applied but no massage received. G2: received a deep-tissue massage of the fore-arm (including effleurage for 2 min and petrissage for 4 min)	6 min	Muscle soreness rating (VAS and PPT), Peak Torque	24–48 h after DOMS induced exercise
7	Xiong et al., 2009	China	20 healthy male untrained students (G1 = 10, G2 = 10). Mean age (SD): G1 = 23.40(2.88) years, G2 = 23.20(2.90) years.	2 sets of eccentric nondominant elbow flexion with 60% maximal isometric force. 25 repetitions for each set with 5 min rest between sets.	G1: no intervention. G2: received Chinese traditional massage (including pushing, swing, grasping, vibrating and plucking) for 30 min each day with 3 days post-exercise.	30 min for every day	Muscle soreness rating, creatine kinase level	0, 24, 48, 72 h after DOMS induced exercise
8	Hu et al., 2010	China	15 healthy male students (G1= 8, G2 = 7). Mean age (SD): G1 = 22.13(3.23) years, G2 = 22.14(3.08) years.	7 sets of 50 m leapfrog with 2–3 min rest between sets.	G1: no intervention. G2: Chinese traditional massage (including pushing, grasping, vibrating and plucking) for 20 min each day with 5 days post-exercise.	20 min for every day	Mucle soreness rating, creatine kinase level, maximal isometric force, Peak Torque at 120°/s	0, 2, 24, 48, 72, 96 h after DOMS induced exercise

(Continued)

TABLE 1 | Continued

No	Article, year	Country/ Region	Subjects' characteristic, sample size	Induce DOMS	Intervention	Duration	Outcomes	Time point
9	Andersen et al., 2013	Canada	20 female volunteers, G1 = 10, G2 = 10. Mean age (SD) for all subjects is 32(11) years.	10 sets of 10–15 repetitions of maximal eccentric contractions of upper trapezius, with 1 min rest between sets.	G1: performed unilateral shoulder shrugs with the Thera-Band elastic tubing. G2: 10 min massage on the trapezius muscle (including petrissage and effleurage) on 48 h after DOMS induced training.	10 min	Mucle soreness rating (VAS and PPT)	0 h after treatment (48 h after DOMS induced training)
10	Imtiyaz et al., 2014	India	30 healthy female non athletic subjects, G1 = 15, G2 = 15. Mean age (SD): G1 = 19.66 (1.01) years, G2 = 20.33 (0.97) years.	30 repetitions of eccentric exercise of elbow flexion using a dumbbell with weight of 80% maximal isometric force.	G1: no intervention. G2: received therapeutic massage for 15 min	15 min	Mucle soreness rating, creatine kinase level, maximal isometric force	24, 48, 72 h after DOMS induced exercise
11	Kargarfard et al., 2016	Iran	30 healthy males with at least 2 years experience in bodybuilding, G1 = 15, G2 = 15. Mean age (SD): G1 = 28.07 (3.33) years, G2 = 29.47 (3.72) years.	Performed squats or leg press to 90° knee flexion for five sets at 75–77% 1RM until exhaustion, with 1 min rest between sets	G1: no intervention. G2: Western massage techniques of effleurage, petrissage and vibration were used for 30 min	30 min	Mucle soreness rating, creatine kinase level, maximal isometric force	0, 24, 48, 72 h after intervention

VAS, Visual analog scale; PPT, pressure pain threshold.

similar between the trials (i.e., 6 min massage for wrist muscles, 30 min massage for lower extremity muscles).

Control Conditions

Most (eight articles) of the studies used no intervention (just sitting for rest). The participants in one study listened to audiotapes while resting, while one study had a thin layer of massage cream applied but no massage received. Another study performed unilateral shoulder shrugs with Thera-Band elastic tubing.

Risk of Bias of Included Studies

Every included study was assessed for the risk of bias according to instructions by Higgins and Green (2011); Higgins et al. (2011). As shown in **Figure 2**, all of the 11 articles used a randomization method, but none of these reported any information about allocation concealment. None of the trials met the requirements for the blinding of participants. However, it seems unfeasible to use the blinding method in view of the massage intervention. Only two studies (18.2%) masked their outcome assessors, which increased the risk of detection bias. Seven studies (63.6%) showed low risk of incomplete outcome bias, and the other four were unclear. Nine studies (81.8%) showed a low risk bias of selective reporting, whereas it was unclear if the studies have additional bias. Funnel plot asymmetry did not show any publication bias of muscle soreness rating, MIF, or the serum levels of CK (Supplemental Figures S1–S3).

Effects of Massage on Muscle Soreness Rating

Four data points (72 participants) reported a muscle soreness rating immediately after strenuous exercise. No significant differences were found when the massage and control groups were compared based on a fixed model (SMD −0.03, 95%CI 0.5–0.44, $P = 0.90$, $I^2 = 0\%$) (**Figure 3A**). Twenty-three data points (504 participants) showed that a muscle soreness rating significantly decreased after the participants received massage intervention when compared with no intervention (SMD −1.16, 95%CI −0.72 to −1.60, $P < 0.001$, $I^2 = 79\%$) (**Figure 3B**). Among these, the muscle soreness rating presented a significant decrease compared to the control group when the participants received massage intervention in subgroups of 24 h (SMD −0.61, 95%CI −1.17 to −0.05, $P = 0.03$, $I^2 = 67\%$), 48 h (SMD −1.51, 95%CI −2.24 to −0.77, $P < 0.0001$, $I^2 = 82\%$) and 72 h (SMD −1.46, 95%CI −2.59 to −0.33, $P = 0.01$, $I^2 = 82\%$) post-exercise, respectively (**Figure 3B**). Based on these results, massage intervention after exercise showed higher efficacy at 48 and 72 h after exercise than at 24 h.

Sensitivity analysis revealed that outcomes of the total effect of muscle soreness rating were stable when trials were removed one by one.

Effects of Massage on MIF

Three data points with 70 participants compared MIF between massage and control groups immediately after intense exercise. No significant difference was observed based on the fixed model meta-analysis (SMD 0.13, 95%CI −0.34 to 0.60, $P =$

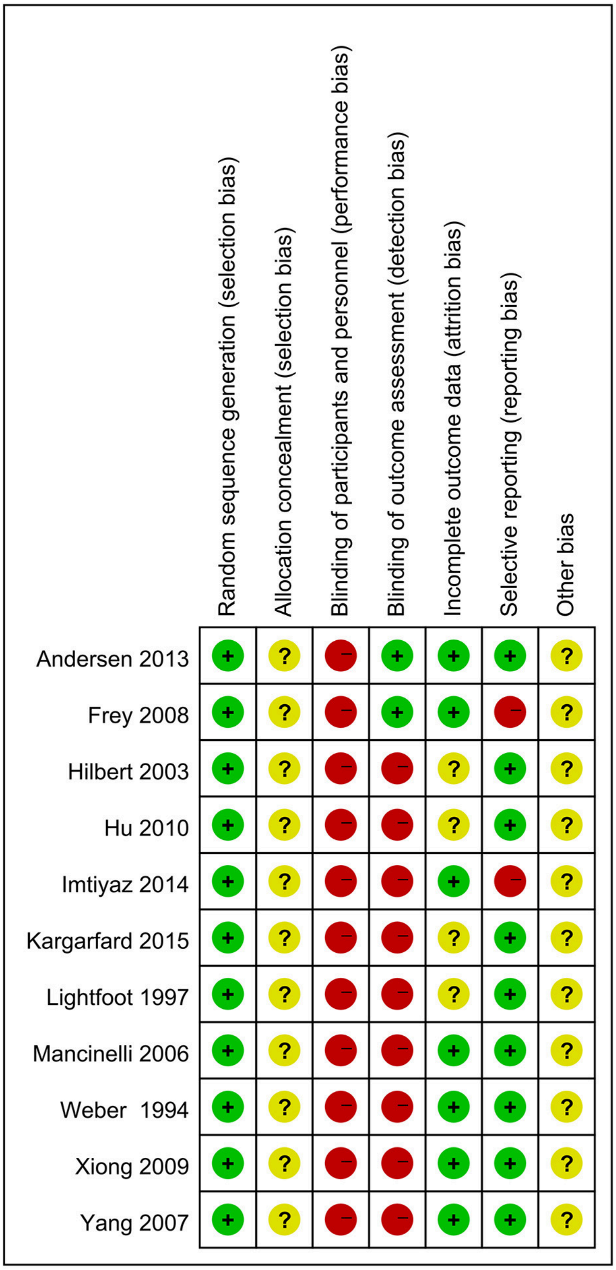

FIGURE 2 | Risk of bias summary of included studies.

0.60, $I^2 = 0\%$) (**Figure 4A**). However, 16 data points (including 265 participants) demonstrated that massage intervention could significantly enhance the performance of MIF compared to controls (SMD 0.56, 95%CI 0.21–0.00, $P = 0.002$, $I^2 = 46\%$) (**Figure 4B**). Among these, only 72 h post-exercise subgroups showed significant positive effects of massage intervention on MIF (SMD 1.11, 95%CI 0.12–2.1, $P = 0.03$, $I^2 = 78\%$). No significant difference of MIF was observed between massage and control groups either at 24 h (SMD 0.34, 95%CI –0.09 to 0.77, $P = 0.12$, $I^2 = 0\%$) or 48 h (SMD 0.31, 95%CI –0.12 to 0.73, $P = 0.16$, $I^2 = 0\%$) post-exercise based on each subgroup meta-analysis.

Sensitivity analysis revealed that outcomes of the total effect of MIF after strenuous exercise were stable when removing trials one by one.

Effects of Massage on Peak Torque

Two data points with 38 participants compared peak torque between massage and control groups immediately after exercise. No significant difference was observed based on the fixed model meta-analysis (SMD –0.26, 95%CI –0.89 to 0.38, $P = 0.43$, $I^2 = 0\%$) (**Figure 5A**). Eight data points (148 participants) as a total effect showed that massage intervention significantly increased peak torque after strenuous exercise when compared to the control group (SMD 0.38, 95%CI 0.04–0.71, $P = 0.03$, $I^2 = 24\%$) though no significant difference was found in the subgroups of 24 or 48 h (**Figure 5B**).

Sensitivity analysis demonstrated that the outcome of peak torque after strenuous exercise was reversed when one of the trials was removed (Hu et al., 2010).

Effects of Massage on Serum CK Level

Five data points with 102 participants reported the outcome of serum CK level comparing massage and control groups immediately after exercise. No significant difference was found between the two groups (SMD 0.12, 95%CI –0.31 to 0.56, $P = 0.58$, $I^2 = 0\%$) based on fixed meta-analysis (**Figure 6A**). Seven articles including twelve data points (including 247 participants) showed that the serum CK level significantly decreased in the massage intervention group when compared to the control group (SMD –0.64, 95%CI –0.25 to –1.04, $P = 0.001$, $I^2 = 54\%$) as a total effect (**Figure 6B**). Among these, the subgroups of 48 and 72 h showed massage intervention could significantly decrease the serum CK level at 48 h (SMD –0.63, 95%CI –1.25 to –0.01, $P = 0.05$, $I^2 = 60\%$) and 72 h (SMD –1.69, 95%CI –3.27 to –0.11, $P = 0.04$, $I^2 = 66\%$) post-strenuous exercise. However, no significant difference was observed in the 24 h subgroup (SMD –0.33, 95%CI –0.75 to 0.09, $P = 0.12$, $I^2 = 9\%$).

Sensitivity analysis showed that outcomes of the total effects of the serum CK levels were stable when trials were removed one by one.

DISCUSSION

Massage therapy intervention is often used for reducing muscle pain or soreness (Field, 2016), and increasing post-exercise muscle performance (Buttagat et al., 2016; Best and Crawford, 2017). Several lines of evidence contributed to explaining the mechanisms of massage therapy on DOMS: (a) modulation of the activity of the parasympathetic nervous system (Weerapong et al., 2005), (b) increase in blood and lymphatic flow to rapidly clear the biochemical markers of muscle damage [e.g., CK and lactate dehydrogenase (LDH); Bakar et al., 2015], (c) psychophysiological response also plays an essential role in reducing pain (Arroyo-Morales et al., 2011).

Best et al. reviewed the effectiveness of massage on muscle recovery including 27 studies and 440 participants, showing

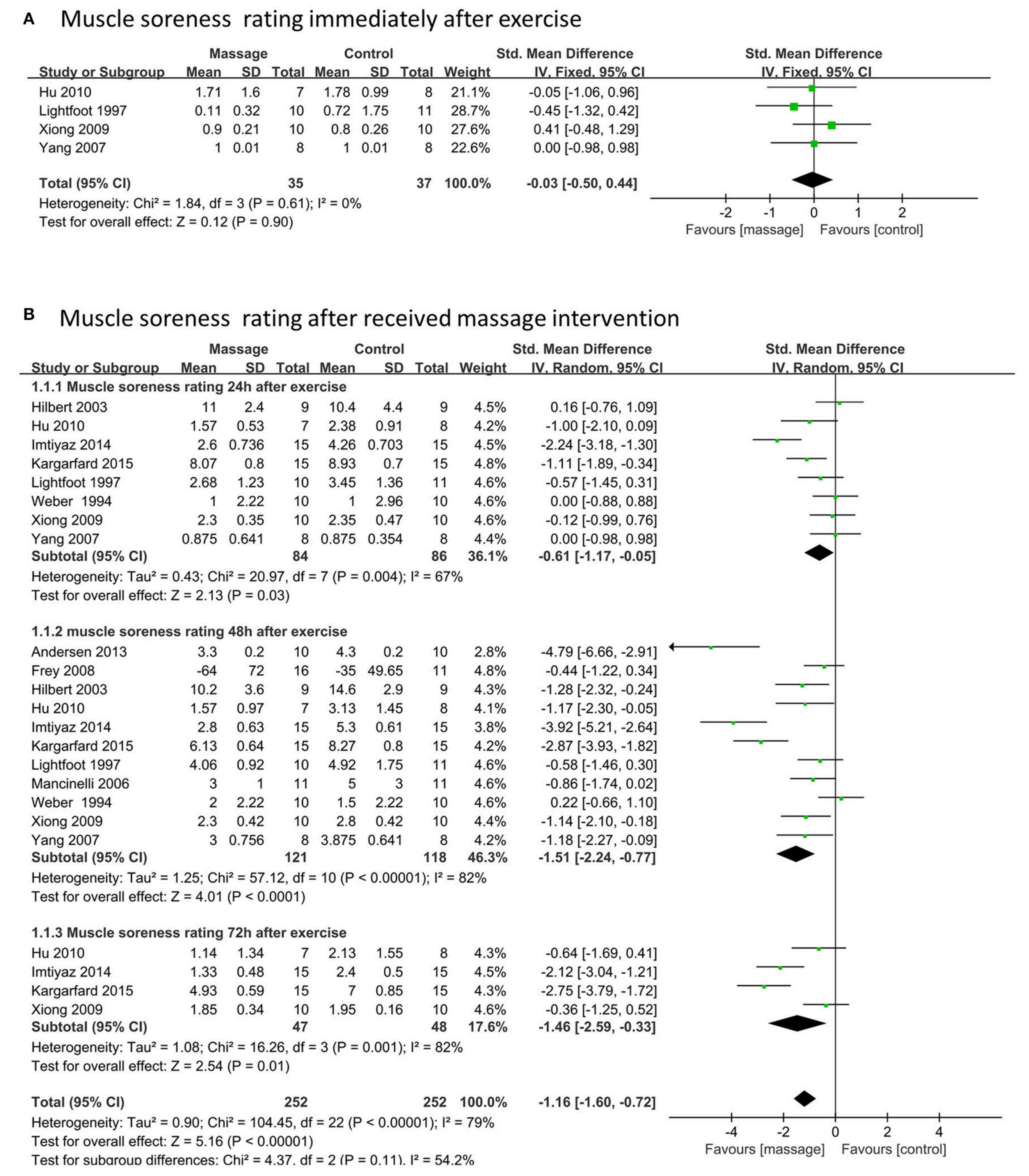

FIGURE 3 | Meta-analysis of effects of massage intervention on muscle soreness rating. **(A)** The time point immediately. **(B)** Time points after received massage intervention combined 24, 48, and 72 h after exercise.

little effect of massage on muscle recovery after intense exercise (Best et al., 2008). However, only six RCTs investigated DOMS and muscle function post-exercise, and in some of the studies, the data could not be extracted for meta-analysis since the published papers did not report the mean and SD. Thus, Best et al.'s review did not pool the extracted data in a meta-analysis.

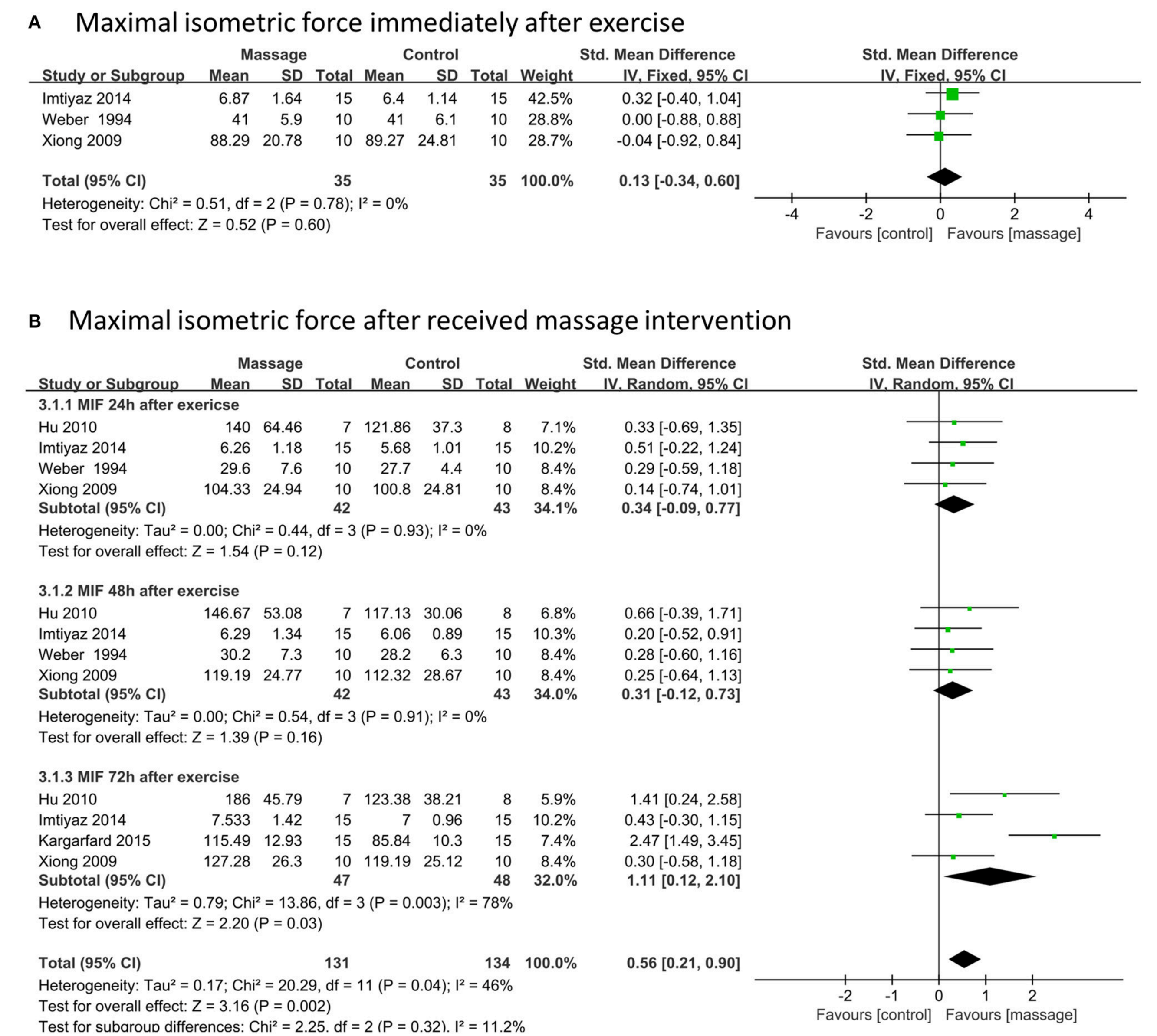

FIGURE 4 | Meta-analysis of effects of massage intervention on MIF. **(A)** The time point immediately. **(B)** Time points after received massage intervention combined 24, 48, and 72 h after exercise. MIF, maximal isometric force.

Torres et al. showed that massage could alleviate muscle soreness 24 h after intense exercise, but few trials were pooled in the meta-analysis (3 trials) (Torres et al., 2012). Other reviews also reported that self-myofascial release (a type of self-massage using a foam roller) could alleviate muscle pain and enhance muscle performance after strenuous exercise (Beardsley and Skarabot, 2015; Cheatham et al., 2015), but no trials were pooled into a meta-analysis to assess the effectiveness. Consistent with previous reviews, the present study confirmed that massage was an effective intervention for reducing DOMS after strenuous exercise with the outcomes of muscle soreness rating, muscle performance (MIF and Peak Torque) and the serum CK level. In addition, it is well known that the evidence from RCTs will be much better than from case studies. Therefore, this review pooled only RCTs in the meta-analysis with a total number of 23 data points (including 504 participants), to be better able to evaluate the effectiveness of massage on DOMS and muscle performance.

This systematic review and meta-analysis showed that the participants receiving massage intervention post-strenuous exercise experienced a reduction in muscle soreness rating as a total effect. Additionally, our findings demonstrated that the SMD of 48 and 72 h subgroups were −1.51 and −1.46, respectively. This result was greater than that of 24 h subgroups (−0.61), indicating that alleviating muscle pain from massage

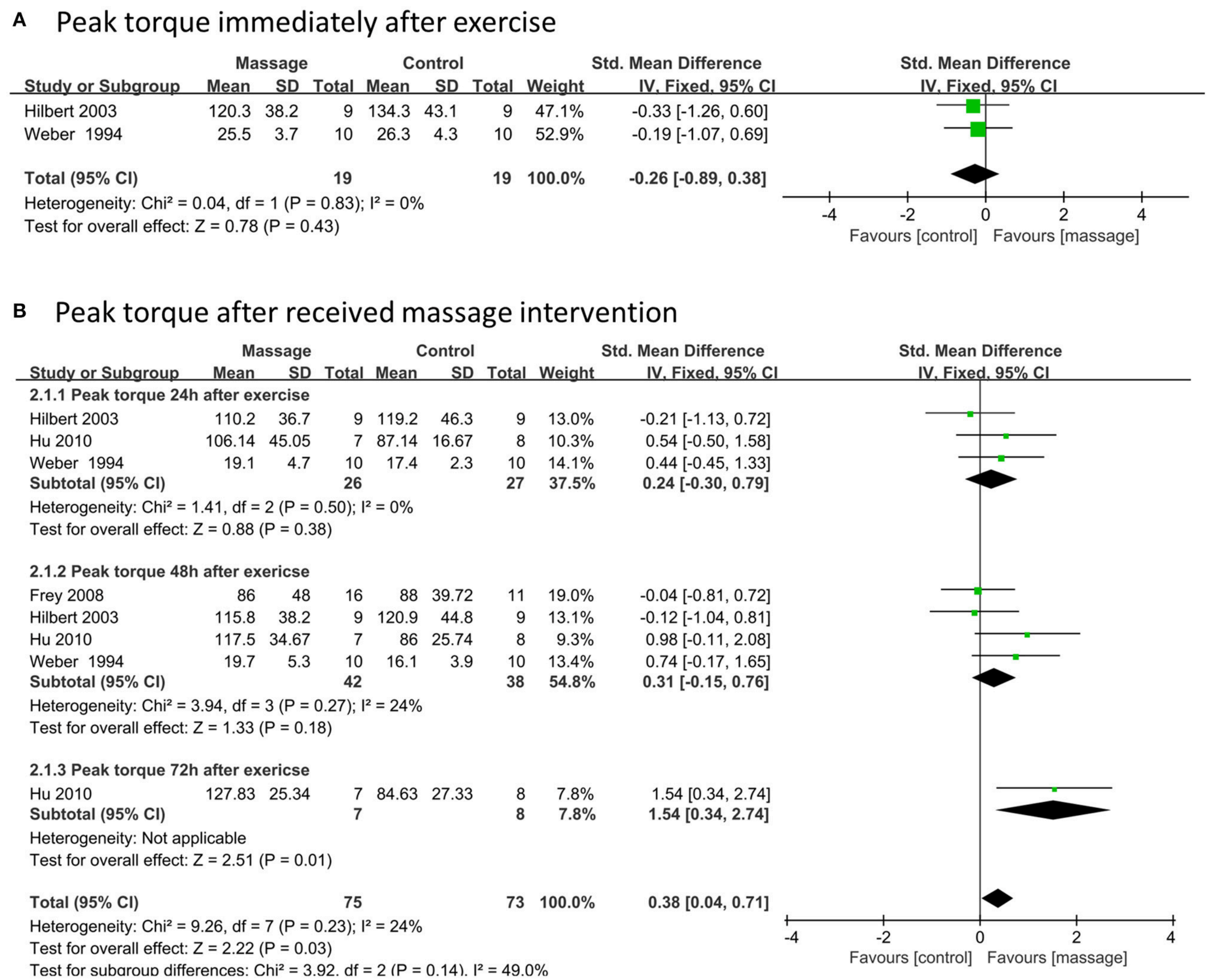

FIGURE 5 | Meta-analysis of effects of massage intervention on peak torque. **(A)** The time point immediately. **(B)** Time points after received massage intervention combined 24, 48, and 72 h after exercise.

intervention would be the more efficacious at 48 and 72 h post-exercise compared to 24 h post-exercise. Moreover, the stability of the total effect sensitivity analysis also strengthened the results.

Previous systematic reviews demonstrated that there was little evidence supporting the use of massage to enhance muscle performance after strenuous exercise (Best et al., 2008; Torres et al., 2012). Poppendieck et al. observed that post-exercise manual massage increased recovery of sprint performance (Poppendieck et al., 2016). However, many articles included in this meta-analysis are not RCTs. in contrast to Best et al.'s and Torres et al.'s reviews, the current evidence showed that massage intervention increased MIF and peak torque after exercise as the total effects. These results may reflect more trials included that had positive effects of post-exercise massage on muscle performance. Three studies (Yang, 2007; Xiong et al., 2009; Hu et al., 2010) using Chinese traditional massage were pooled in this meta-analysis. The single effects of those trials were not different from those of the trials using Western massage. In addition, two studies (Xiong et al., 2009; Hu et al., 2010) used daily massage and one study (Mancinelli et al., 2006) applied massage 48 h post-exercise, however the effects of these single trials were not different from the others. Conversely, the effectiveness of single trials is not enough to show significant benefits of massage intervention on muscle performance post-strenuous exercise. Additional trials and participants are needed. Furthermore, contrary to Poppendieck et al.'s review, which included studies using endurance-type exercise, most of the studies included in this review used eccentric strength exercise to induce DOMS, which may also contribute to the difference between this meta-analysis and that of previous reviews.

The serum CK level was frequently considered a marker of inflammation and skeletal muscle damage influencing the recovery of muscle performance (Clarkson and Sayers, 1999; Romagnoli et al., 2015). Our findings showed that massage

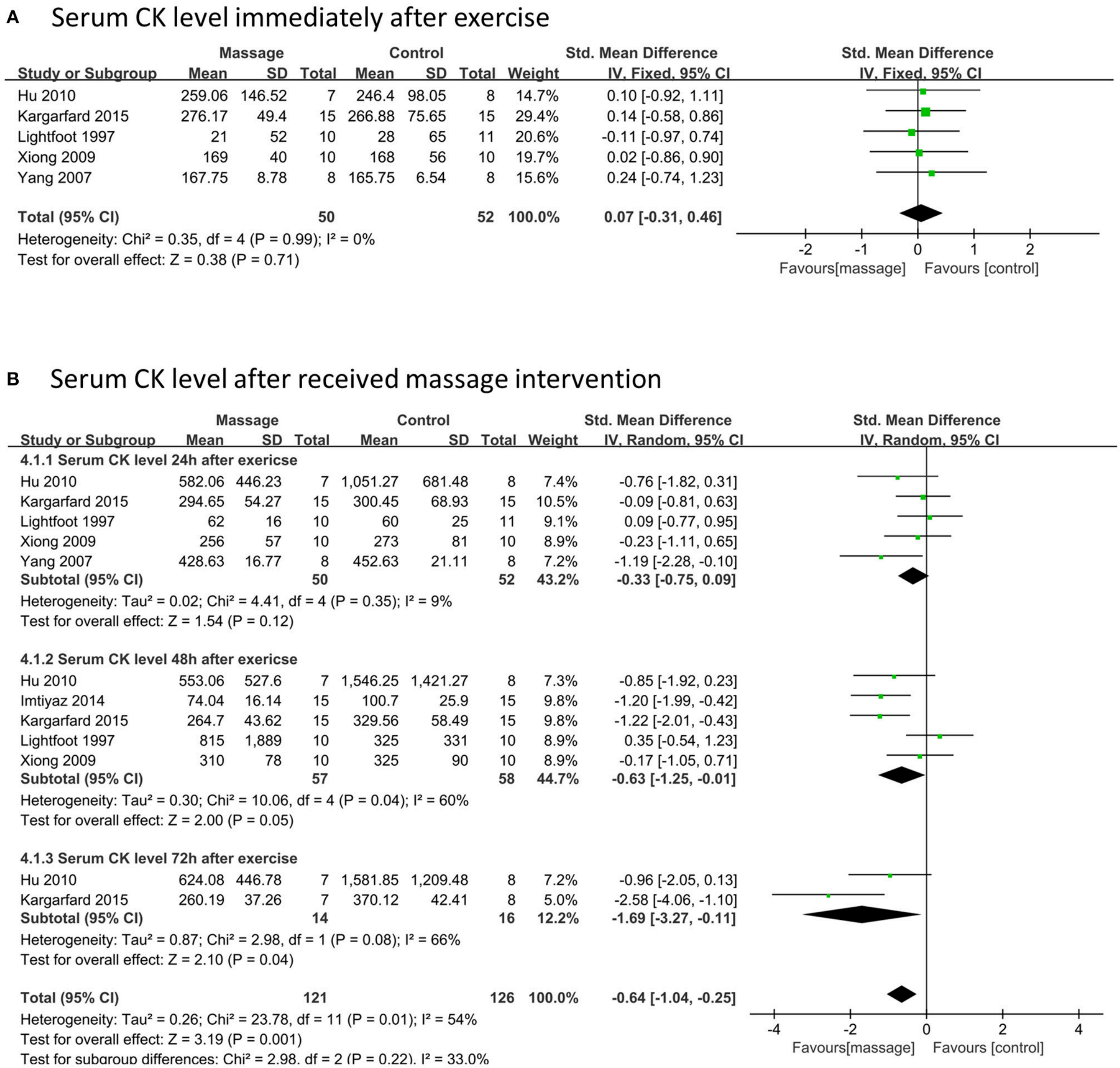

FIGURE 6 | Meta-analysis of effects of massage intervention on the serum CK level. **(A)** The time point immediately. **(B)** Time points after received massage intervention combined 24, 48, and 72 h after exercise. CK, creatine kinase.

intervention decreased the serum CK levels as a total effect, suggesting that massage decreased inflammation and muscle damage and promoted muscle performance recovery. This result is consistent with the results of muscle soreness rating, MIF, and peak torque, supporting evidence of the positive physiological effects of massage therapy on DOMS. Fast clearance of serum CK level from the circulatory system was thought to be the reason that massage promotes muscle recovery and performance.

Strength and Limitations

This study is the first meta-analysis that combines both Chinese and Western massage at different time points after strenuous exercise, assessing whether massage intervention was effective in alleviating DOMS. Compared with previous studies, the present study included three articles using Chinese traditional massage intervention and more trials were pooled into the meta-analysis than in previous systematic reviews. This strategy implied greater evidence to evaluate the effectiveness of massage intervention after exercise. Furthermore, current evidence suggests that massage is not only effective in reducing muscle pain after intense exercise, but also in increasing muscle performance and reducing the serum CK level.

This review searched a wide variety of database including two Chinese electronic databases for relevant articles and included the trials performing Chinese traditional massage that have not previously been reviewed. Two authors independently searched and selected the included studies, extracted the data, and assessed the risk of bias of every trial using recommended protocols and methodological schemes. Therefore, the results of this meta-analysis are considered a significant contribution.

However, this meta-analysis has several limitations. First, the quality of all the included trials in this meta-analysis was low. None of the studies detailed allocation concealment although all the trials used a randomization method. None of the studies met the blinding of participants though it seems unfeasible to use the blinding method in view of the massage intervention. This factor increased the selection bias and performance bias. Only two articles (18.2%) masked their outcome assessors, which increased the risk of detection bias. Second, the trials varied in methodological design (i.e., exercise type, control intervention), massage type, and conditions (i.e., duration). Thus, the outcomes of muscle soreness have high heterogeneity although the total effects of outcomes were stable. Sensitivity analysis implied that the outcome of peak torque after strenuous exercise was unstable; therefore, the results should be considered with caution. Third, there may be some publication bias as unpublished articles could not be searched in this review although the funnel plot asymmetry did not show the bias. Finally, the number of trials and participants was relatively small; therefore, larger sample sizes in future studies are needed to better understand the effects of massage intervention on DOMS and muscle performance.

CONCLUSION

This systematic review and meta-analysis demonstrated that massage intervention could be effective for alleviating DOMS, as well as increasing muscle performance after strenuous exercise. The highest efficacy was achieved at 48 h post-exercise. Massage is a useful and practical therapy for exercise participants or athletes. Nevertheless, it is necessary to be cautious about the results in view of the limitations outlined in the present study. More RCTs with large sample sizes are needed for better understanding the effectiveness of massage intervention on DOMS and muscle performance.

AUTHOR CONTRIBUTIONS

XC and JZ designed the systematic review and supervised the entire program; JG and LL reviewed all the studies and extracted the information from the eligible trials; YG analyzed the data and prepared the figures and table; XC, JG, and LL wrote the paper; XC, RZ, and JX revised the manuscript. All authors reviewed and approved the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fphys.2017.00747/full#supplementary-material

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Upper-Body Muscular Endurance Training Improves Performance Following 50 min of Double Poling in Well-Trained Cross-Country Skiers

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This study investigated the effect of muscular endurance training on O_2-cost and performance in double poling (DP) on a rollerski treadmill. Twenty-two well-trained cross-country skiers (31 ± 4 years, 77 ± 9 kg, 181 ± 8 cm, VO_{2max} running: 64 ± 5 mL·kg^{-1}·min^{-1}) were counter-balanced to either a combined muscular endurance and running interval training group [MET; $n = 11$ (♂ = 9, ♀ = 2)], or an endurance running interval training group [ET; $n = 11$ (♂ = 9, ♀ = 2)]. Both groups continued their normal low-and moderate intensity training, but replaced 2 weekly high intensity-training sessions with two project-specific sessions for 6 weeks. In these sessions, MET combined upper-body muscular endurance training (4 × 30 repetitions, 90 s rest between sets) and running intervals (3 × 4 or 2 × 6 min, 3 min rest), while ET performed running intervals only (6 × 4 or 4 × 6 min, 3 min rest). The DP test-protocol consisted of 50 min submaximal poling for O_2-cost measurement, followed by a self-paced 1,000-m performance test. In addition, subjects performed a VO_{2max} test in running. MET increased muscular endurance ($P < 0.05$) and 1RM in simulated DP ($P < 0.01$) more than ET. Further, MET reduced the 1,000-m time and O_2-cost compared to baseline values ($P < 0.05$), and tended to improve the 1,000-m time more than ET ($P = 0.06$). There were no changes in VO_{2max} running or VO_{2peak} DP in either MET or ET. In conclusion, 6 weeks of muscular endurance training increased both muscular endurance and 1RM in simulated DP. Further, specific upper-body muscular endurance training improved DP performance and thus, seems as a promising training model to optimize performance in well-trained cross-country skiers.

Keywords: cross-country skiing, high-intensity training, maximal oxygen uptake, O_2-cost, running, training intensity

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INTRODUCTION

In cross-country (XC) skiing, the classic style double poling (DP) technique has been considerably developed over the last decade and is today the main technique used in races. The DP technique is characterized by a symmetrical DP action, which transfers propulsive forces solely through the poles. This emphasizes the importance of well-developed upper-body power in employing DP successfully throughout an entire race (Stöggl et al., 2007; Losnegard et al., 2011). Consequently, specific upper-body training, both in research and practical situations, has gained interest as a training model for improving such abilities (Nilsson et al., 2004; Terzis et al., 2006; Losnegard et al., 2011; Skattebo et al., 2015).

The introduction of new competition formats such as sprint and mass starts has also increased the importance of a high work-intensity during the closing part of races, which makes it vital to conserve power for the final sprint. This requirement could potentially be met by working at a lower relative intensity during the submaximal part of the competition, resulting in less fatigued muscles during the final sprint (Bassett and Howley, 2000). However, limited data are available on which type of training is most efficient in improving such abilities in XC skiing generally and DP more specifically.

In previous research, the main training model for developing upper-body power to improve DP performance has been heavy strength training (≤12 repetition maximum). However, these studies have yielded varying results, displaying both large (Hoff et al., 1999, 2002; Østeras et al., 2002) and trivial effects (Losnegard et al., 2011; Skattebo et al., 2015). Furthermore, the metabolic response during DP seems to be different for the arms and legs, indicating that intense upper-body endurance training may increase the arms' ability to extract oxygen and thus enhance DP performance (Rud et al., 2014).

The effect of muscular endurance training (20–100 reps/set, Campos et al., 2002) on endurance performance has been investigated in various sports including running (Mikkola et al., 2011; Sedano et al., 2013) and rowing (Ebben et al., 2004; Gallagher et al., 2010). Such training seem to target different muscular and neurological adaptations compared to heavy strength training; e.g., mitochondria and capillary density, muscle fiber composition and cross-sectional area (Campos et al., 2002). Specifically for XC skiing, Nilsson et al. (2004) showed that 20-s or 180-s interval training in a DP ergometer increased both 30-s and 6-min power output in well-trained XC skiers, while Vandbakk et al. (2017) demonstrated increased time to exhaustion after 8 weeks of 30-s DP intervals. This indicates that upper-body power training might have the potential to increase performance in XC skiing, although data on the effect on finishing abilities is limited.

In terms of training, three variables (intensity, duration, and frequency) together set the training load with the explicit goal of maximizing performance (Seiler, 2010). When investigating the effect of a specific training program for recreational athletes, often with limited time to execute training, it seems important to keep the three variables similar before and during interventions to determine the effect of the intervention itself. Otherwise, it could be unclear whether improved performance is a result of adaptations related to the added training, or changed training load in general. The aim of the present study was, therefore, to investigate the effect of replacing parts of high intensity interval training with muscular endurance training for 6 weeks on performance after completing 50 min of submaximal DP. The main hypotheses of the present study were; Upper body muscular endurance training would (I) improve performance following 50-min of double poling, and (II) reduce O_2-cost during submaximal double poling.

MATERIALS AND METHODS

Subjects

During the intervention, two men withdrew from the project due to unrelated reasons. In total, 22 well-trained XC skiers (18 males and 4 females) completed the study with the required number of completed project-specific training sessions (minimum adherence 85%; MET = 94 ± 8% adherence; ET = 90 ± 5% adherence). Inclusion criteria were completing the long-distance XC ski race *Birkebeinerrennet* the previous year with a finishing time <4 h and < 3 h 30 min for females and males respectively. None of the subjects performed specific upper-body muscular endurance training systematically prior to the start of the study, but all performed weekly aerobic high-intensive interval training. After completing the pre-test, participants were counter-balanced to either a muscular endurance training group (MET: 30 ± 4 years, 76 ± 8 kg, 180 ± 7 cm) or an endurance training group (ET: 32 ± 4 years, 78 ± 11 kg, 182 ± 10 cm) based on the following pre-test characteristics: DP 1,000-m time, VO_{2max} running, 1 repetition maximum (1RM) and gender. All skiers gave their written informed consent before participating. The study was conducted according to the Declaration of Helsinki and Norwegian law.

Design

The investigation was conducted during the pre-competition period for XC skiers (August–November), and contained a 6-week intervention period, enclosed by a pre- and post-test (**Table 1**). The week before pre-tests, subjects performed one familiarization session on the rollerski treadmill which consisted of three different submaximal speeds, followed by a 1,000-m performance test (see *Prolonged double poling protocol*). Then, a familiarization session with the muscular endurance exercise in standing DP was performed, using the cable-pulley and consisted of a warm-up and 1RM test (2–3 attempts). Pre- and post-tests were conducted in the week immediately before and after the training period and included 2 test days for each participant, separated by at least 48 h. Subjects were not allowed to perform any strength training the day before testing, and only a maximum of 90 min endurance training at low intensity. Day 1 included a running VO_{2max} test followed by an upper-body 1RM and a muscular endurance test in a cable-pulling apparatus. Day 2 included a submaximal and maximal test in DP on a rollerski treadmill. During the intervention period, both groups replaced two of their weekly high-intensity interval training (HIT) sessions with a specific protocol based on their respective group. For MET, these sessions consisted of both running intervals and upper-body muscular endurance training, while for ET it involved two sessions with running intervals only. During the other weekly training sessions, the subjects were encouraged to maintain their normal training routines.

Running VO_{2max} (Day 1)

Following a 20-min warm up (60–85% of HR_{peak}), subjects performed a VO_{2max} running test at a 10.5% incline with stepwise increments of 1 km-h^{-1} every minute until volitional exhaustion. Starting speed was set individually based on subjects' race history

TABLE 1 | The test-battery and time-line of the study.

Familiarization	x								
Test day 1:									
VO_{2max} running test		x							x
1RM- and muscular endurance test		x							x
Test day 2:									
Double poling protocol		x							x
		Pre-test ⟷			Intervention ⟵	⟶			Post-test ⟷
Week:	–2	–1	1	2	3	4	5	6	7

VO_{2max}, maximal oxygen uptake; RM, repetition maximum.

(average: 9.4 ± 0.7 km-h^{-1}), but was similar for each subject at pre- and post-test. All tests lasted 4.5–7.5 min, and the highest VO_2 over a 60 s period was considered as VO_{2max}.

Maximal Strength and Muscular Endurance (Day 1)

Fifteen minutes after the running VO_{2max} test, the subjects performed an exercise-specific warm-up in the standing DP, consisting of four sets (15 reps at 40%, 10 reps at 55%, 5 reps at 75%, 3 reps at 85% of 1RM as estimated during familiarization). In the 1RM test, the load was set to 95% of estimated 1RM (at post-test, 95% of pre-test 1RM was used), and increased 2–5% after each successful attempt (3 min break) until the subject failed on two consecutive lifts. The heaviest successful attempt was considered 1RM. After a 5 min break, the muscular endurance test was conducted at 55% of individual 1RM. This relative workload was set based on pilot testing and previous studies, with the aim of completing more than 20, but less than 100 repetitions (Stone and Coulter, 1994; Campos et al., 2002). The test was performed using a constant DP motion (cycle time; pre 1.4 ± 0.2 s; post 1.4 ± 0.2 s, based on video recording) until exhaustion. All testing and training with the cable-pulley was done with a customized handlebar to simulate a DP grip (**Figure 1**).

FIGURE 1 | The standing double poling exercise used during testing and training. The figure illustrate the poling phase of the cycle. The participant gave his consent to publish the picture.

Prolonged Double Poling Protocol (Day 2)

The protocol was initiated by a 5 min trial identical to the first submaximal speed to ensure a steady state oxygen uptake at the first submaximal load. Further, subjects performed three different submaximal speeds (50 min total), followed directly by a 1,000-m test (**Figure 2**). All DP tests were conducted at 2.5°. Submaximal speeds were based on the linear relationship between workload and O_2-cost, with the aim of matching speed to 75% of VO_{2peak} DP from 15 to 50 min and adjusted with the RPE (rate of perceived exertion, Borg, 1982) with the aim of not exceeding 16 on the RPE-scale before the 1,000-m test. Thus, speeds were individually set, but were identical for each participant in the pre- and post-test. The average speed for all participants at submaximal speeds one, two and three was 2.3 ± 0.3, 2.7 ± 0.4 and 3.0 ± 0.5 m·s^{-1}, respectively. The O_2-cost was calculated from 8-10, 13-15, 18-20, 33-35 and 48-50 min during the prolonged submaximal test. Heart rate (HR) was registered after 10, 15, 20, 35, and 50 min and RPE after 20, 35, and 45 min. The 1,000-m test was a modified protocol from Losnegard et al. (2013). In brief, a fixed individual speed, identical at pre- and post-test, was set for the initial 200 m to avoid over-pacing (avg. 3.41 ± 0.5 m·s^{-1}). Thereafter, the subjects were free to adjust their speed based on their position on the treadmill (0.25 m·s^{-1} increase or decrease). VO_2 and HR were measured continuously, and the highest VO_2 and HR (avg. 30 s) were considered peak values. RPE was reported immediately after finishing the test. During the prolonged exercise, participants were asked to drink 3 dl of water.

Apparatus

Oxygen consumption was measured with an automatic ergospirometry system (Oxycon Pro, Jaeger Instrument, Hoechberg, Germany), as evaluated by Foss and Hallen (2005). The gas analysers and the flow turbine (Tripel V; Erick Jeager GmbH, Hoechberg, Germany) were calibrated before each test according to the instruction manual, as described previously (Losnegard et al., 2011). The same gas analyser was used during the running VO_{2max} test and DP protocol. Heart rate was recorded using a Polar V800 (Polar Electro Oy, Kempele, Finland). A rollerski treadmill with belt dimension 3 × 4.5 m (Rodby, Södertelje, Sweden), was used during the running VO_{2max} test and the prolonged DP test. Two different pairs of rollerskis (Swenor Fiberglass, Trøsken, Norway), with front wheel type 2 and rear wheel type 3, were used depending on which ski binding system the skiers used (SNS, Salomon, Annecy, France or NNN, Rottefella, Klokkarstua, Norway). The rollerski

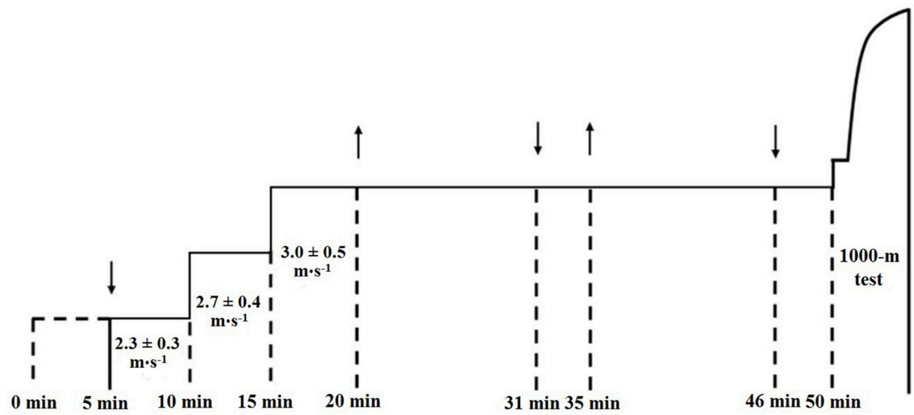

FIGURE 2 | Schematic illustration of prolonged double poling protocol. Steady-state VO_2 was measured from 5 to 20, 31 to 35, and 46 to 50 min followed by a self-paced 1,000-m maximal test. ↓ = start O_2 measurements. ↑ = end O_2measurements. All tests conducted at 2.5° incline and the speed shown is the average from both groups. Speed from 0 to 5 min was identical to 5 to 10 min.

TABLE 2 | Training programs for the 2 weekly project sessions in MET (Combined endurance training and muscular endurance training) and ET (endurance training).

Week	MET					ET	
	Running interval		Muscular endurance			Running interval	
	Duration (sets × min)	Intensity (% HR_{peak})	Sets	Rep	Workload (% 1 RM)	Duration (sets × min)	Intensity (% of HR_{peak})
1–2	3 × 4/2 × 6	88–92	4	30	42.5	6 × 4/4 × 6	88–92
3–4	3 × 4/2 × 6	88–92	4	30	45	6 × 4/4 × 6	88–92
5–6	3 × 4/2 × 6	88–92	4	30	47.5	6 × 4/4 × 6	88–92

During running intervals, a 3 min rest was applied.
HR_{peak}, peak heart rate; RM, repetition maximum.

friction coefficient was 0.026 before, during and after the project, and tested as described in Hoffman et al. (1990). All participants used Swix Triac 1 poles (Swix, Lillehammer, Norway), with customized tips for rollerski treadmills (self-selected pole length for all tests; 153.3 ± 7.7 cm, corresponding to 82 ± 3% of body height). A cable-pulley machine (Technogym Cable Jungle, Gambettola, Italy), with a 45 cm-wide custom-made handlebar (Losnegard et al., 2011) was used during training and tests in the standing DP. Cycle times during submaximal DP (after 21 and 41 min) and the muscular endurance test were recorded (Sony DCR-TRV900E; Sony, Tokyo, Japan).

Training

A description of the specific training sessions is provided in **Table 2**. The training sessions lasted approx. 50 min, including a 10 min warm-up. Running intervals lasted 4 or 6 min with 3 min rest periods in-between. During the muscular endurance training, there was a passive rest of 90 s between sets. Speed during running intervals was based on individual HR_{max} measured during the VO_{2max} running test, and adjusted to match the intended HR-zone within 90 s of trial-start (88–92% of HR_{max}) (Helgerud et al., 2007). The intended intensity has previously been shown to be advantageous in increasing the maximal oxygen uptake in well-trained athletes (Seiler et al., 2013). All subjects where individually supervised during the 1st, 5th, and 9th training session to ensure proper intensity during intervals. Additionally, MET was observed in simulated DP to ensure proper technique and the load was adjusted according to **Table 2**. All training from the 4 weeks prior to the beginning of the intervention until the end of the intervention period were reported. The endurance training intensity was divided into three HR zones: low-intensity (LIT; 60–81% of peak HR_{max}), moderate-intensity (MIT; 82–87%) and high-intensity training (HIT 88–100%), based on intensity zones developed by the Norwegian Olympic Federation.

Statistical Analysis

All data are presented as mean ± standard deviation (SD). Baseline differences between groups were tested with unpaired Student's t-tests. Within-group and between-group changes were tested with paired Student's t-tests and two-way repeated-measures analysis of variance (ANOVA), respectively. All statistical analysis was performed using Excel 2003 (Microsoft Corporation, Redmond, Washington, USA) and IBM SPSS Statistics 20 (International Business Machines, New York, USA). The level of confidence was set to 90% and $P \leq 0.05$ were considered statistically significant, while $0.05 < P \leq 0.1$ was considered a tendency toward statistical significance.

RESULTS

Training

There was a tendency toward differences between groups in total training volume prior to the training intervention ($P = 0.10$), mainly due to a higher volume of LIT in MET compared to ET (**Table 3**). There were no differences in the intensity-zone distribution between pre-intervention and intervention in MET. In ET, there was a small, but significant (0.1 h) increase in total training volume of HIT per week from pre-intervention to intervention.

Muscular Endurance and Maximal Strength

MET improved muscular endurance by 21 ± 8% (mean ± 90% confidence interval) while no changes occurred in ET (−1 ± 11%), resulting in a 22 ± 8% difference between groups (**Figure 3A**). Individual differences from pre- to post-test are shown in **Figure 7B**. 1RM increased significantly in MET (6 ± 2%) and tended to increase in ET (2 ± 3%; $P = 0.05$), with a significant group difference of 4 ± 4% (**Figure 3B**).

1,000-m Time

The mean 1,000-m time decreased in MET (−4 ± 2%), but was unchanged in ET (−1 ± 2%, **Figure 4**), which resulted in a between-group difference of 4 ± 2% ($P = 0.06$). Individual differences from pre- to post-test are shown in **Figure 7A**. From pre- to post-test, MET increased speed more than ET between 500 and 700-m (7 ± 1%), and there was a tendency to difference between groups at intervals 200–400-m (5 ± 1%, $P = 0.08$) and 700–800-m (5 ± 1%, $P = 0.08$) (**Figure 5**).

Physiological Responses during 1,000-m Time and VO_{2max} Running

VO_{2max} running and VO_{2peak} DP was unchanged from pre- to post-test in both groups (**Table 4**). Individual changes in VO_{2peak} DP are shown in **Figure 7C**. The percent differences between VO_{2peak} DP and VO_{2max} running were 89 ± 3% in MET and 89 ± 2% in ET at both pre- and post-test. There was a tendency toward increase in HR_{peak} DP in MET (2 ± 1%; $P = 0.06$), while ET remained unchanged

TABLE 3 | Training distribution (hours per week) in the 4 weeks prior to pre-test (Pre-intervention) and during the 6-week intervention period for MET ($n = 11$) and ET ($n = 11$).

Variable	MET		ET	
	Pre-intervention	Intervention	Pre-intervention	Intervention
LIT (60–81% of HR_{peak})	6.4 ± 3.1	5.6 ± 2.9	4.3 ± 2.2	4.1 ± 2.3
MIT (82–87% of HR_{peak})	1.2 ± 0.6	1.2 ± 0.7	1.0 ± 0.5	1.0 ± 0.6
HIT (88–100% of HR_{peak})	0.5 ± 0.2	0.6 ± 0.3	0.6 ± 0.3	0.7 ± 0.2*
Total endurance training	8.1 ± 3.6	7.5 ± 3.3	5.9 ± 2.1	5.8 ± 2.0
Muscular endurance training	–	0.3 ± 0.1	–	–
Strength training	0.5 ± 0.7	0.5 ± 0.5	0.3 ± 0.4	0.4 ± 0.5
Total training	8.6 ± 4.6	8.3 ± 4.2	6.2 ± 3.2	6.2 ± 3.1
Double poling	3.3 ± 2.7	2.4 ± 2.4	1.5 ± 1.1	1.2 ± 0.8

LIT, low-intensity training; MIT, moderate intensity training; HIT, high-intensity training; MET, combined muscular endurance and endurance training group; ET, endurance training group.
**Significant in-group difference from pre-intervention to intervention (P < 0.05). Double poling is performed during rollerski.*

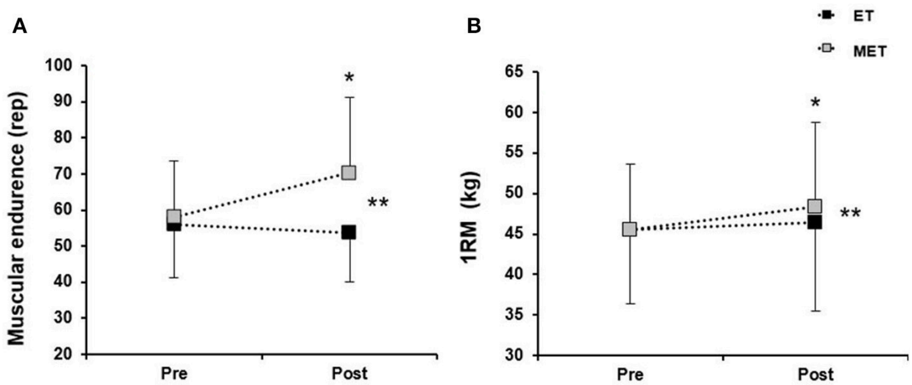

FIGURE 3 | Muscular endurance **(A)** and 1RM **(B)** in the standing double poling exercise before (pre) and after (post) 6 weeks of combined endurance- and muscular endurance training (MET) or endurance training (ET). Data are expressed as group mean ± standard deviation. *Significant change from pre- to post-test ($P < 0.05$). **Significant differences from pre- to post-test between MET and ET ($P < 0.05$).

(−1 ± 1%), resulting in a significant difference of 3 ± 1% between groups. Rating of perceived exertion (RPE) after the 1,000-m test was unchanged from pre- to post-test in both groups.

Physiological Response during Submaximal Double Poling

The average O_2-cost for all five submaximal measurements were reduced in MET from pre- to post-test, (−2 ± 2%) mainly due to reduced O_2-cost after 15 (−3 ± 2%) and 20 min (−2 ± 1%, **Figure 6A**). No significant change was found in ET for mean O_2-cost (−1 ± 1%), or at any specific time-point (**Figure 6B**). For both groups, individual changes in average O_2-cost are shown in **Figure 7C**. However, there was no significant change between groups in mean O_2-cost or O_2-cost for single time measurements. There was a decrease in RER in MET after 35 min (−2 ± 1%, **Figure 6C**), and in ET after 15 (−2 ± 1%) and 35 min (−2 ± 1%, **Figure 6D**), resulting in a larger decrease in ET than in MET after 15 min (2 ± 1%). Heart rate remained unchanged from pre- to post-test for both groups (**Figures 6E,F**). Cycle time was not different from pre- to post-test both within and between groups.

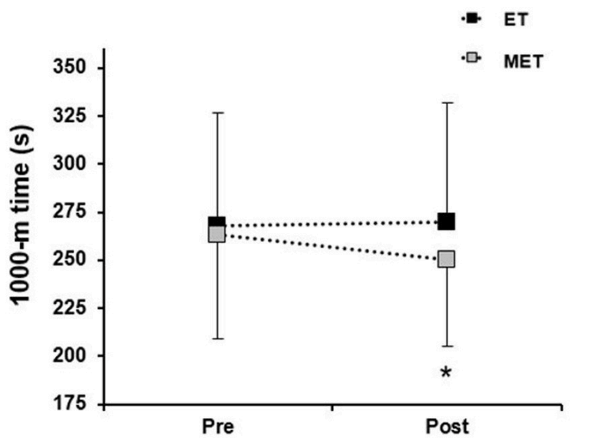

FIGURE 4 | 1,000-m time before (pre) and after (post) 6 weeks of combined endurance training and muscular endurance training (MET) and endurance training (ET). Data are expressed as group mean ± standard deviation. *Tendency to change from pre- to post-test ($P = 0.06$).

DISCUSSION

This study investigated the effect of replacing parts of high-intensity interval training with upper-body muscular endurance training in well-trained XC skiers. The principal findings were: (I) Six weeks of muscular endurance training increased muscular endurance and maximal strength in a simulated DP exercise. (II) MET tended to improve 1,000-m DP performance after 50 min of submaximal DP compared to ET. (III) MET reduced the O_2-cost during submaximal DP, but it was not significant different from ET. (IV) No changes in VO_{2peak} DP or VO_{2max} running were found in either group.

A novel finding of the present study was that upper-body muscular endurance training improved 1,000-m poling time completed immediately after 50 min of submaximal DP. In a similar study, but with a slightly different training model, Nilsson et al. (2004) found a significant improvement in mean power output during a 6-min all-out test after 6 weeks of 20-s DP interval training. Moreover, Vandbakk et al. (2017) showed that 30-s DP intervals over ∼8 weeks resulted in improved time to exhaustion in the interval group, but not in the control group. Together, these studies indicate that short-term upper-body endurance training may be a promising training model and, thus, have direct applications for well-trained skiers aiming to improve their DP performance. However, whether these findings on an indoor treadmill are valid on snow needs to be examined.

The improved 1,000-m time should be a result of improved energy turnover and/or reduced O_2-cost (Bassett and Howley,

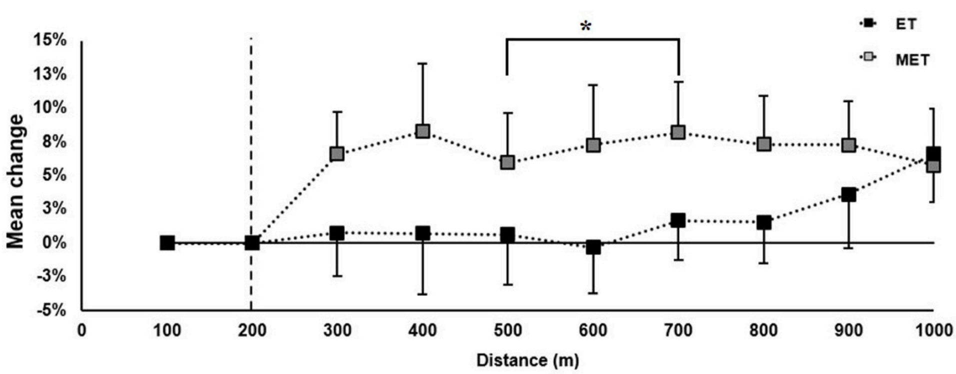

FIGURE 5 | Relative change in speed during the 1,000-m time trial from pre- (black horizontal line at 0%) to post-test. Data are expressed as group mean ± standard deviation. The speed was set the first 200 m. All tests conducted at 2.5° incline. *Significant differences from pre- to post-test between combined endurance training and muscular endurance training (MET) and endurance training (ET) ($P < 0.05$).

2000). No significant changes were measured in aerobic energy turnover in either group while the anaerobic capacity was not estimated (due to methodology). However, the relative change in O_2-cost during prolonged DP was in favor the group that had trained upper-body muscular endurance, possibly contributing to the enhanced performance due to a lower level of fatigue before the 1,000-m time. These findings are in accordance with Rønnestad et al. (2011) who showed increased 5 min all-out performance following 185 min of cycling after a heavy strength training intervention. However, mechanisms for increase in work economy, when including heavy strength training or muscular endurance training, remain unclear. Furthermore, in both the present study and in Rønnestad et al. (2011) the reduction in O_2-cost should be taken with caution since the relative differences in O_2-cost between groups was not significant.

The ratio VO_{2peak} DP/VO_{2max} running was ∼90% at pre-test, which is similar to other studies (Rud et al., 2014; Skattebo et al., 2015). However, no changes were observed in either group, a finding consistent with most studies on heavy strength training, short-term speed training or endurance training in XC skiing (Hoff et al., 1999; Østeras et al., 2002; Nilsson et al., 2004; Rønnestad et al., 2012; Skattebo et al., 2015). Thus, reducing this "gap" has been speculated to be one of the

TABLE 4 | Physiological response during the 1,000-m time test (MET: $n = 11$; ET: $n = 10$) and running VO_{2max} test (MET: $n = 11$; ET: $n = 11$). Data are mean ± standard deviation.

Variable	MET		ET	
	Pre	Post	Pre	Post
1,000-m TIME				
VO_{2peak} (mL·kg^{-1}·min^{-1})	57.2 ± 6.7	58.0 ± 6.3	56.2 ± 5.8	57.7 ± 6.7
VO_{2peak} (L·min^{-1})	4.5 ± 0.8	4.4 ± 0.8	4.3 ± 0.7	4.4 ± 0.8
HR_{peak} (beat ·min^{-1})	184 ± 4	187 ± 6**	190 ± 8	188 ± 5
RPE (6–20)	18.5 ± 1.0	18.5 ± 1.5	19.0 ± 1.0	18.5 ± 1.0
RUNNING VO_{2max} TEST				
VO_{2max} (mL·kg^{-1}·min^{-1})	64.1 ± 5.1	64.7 ± 5.6	63.2 ± 5.2	63.9 ± 5.0
VO_{2max} (L·min^{-1})	4.9 ± 0.8	5.0 ± 0.8	4.9 ± 0.9	4.9 ± 0.9
HR_{peak} (beat ·min^{-1})	190 ± 5	188 ± 5	190 ± 8	188 ± 8*
RPE (6–20)	18.5 ± 1.0	19.0 ± 1.0*	19.0 ± 0.5	19.0 ± 1.0

*MET, Combined muscular endurance and endurance training group; ET, endurance training group. *Significant in-group difference from pre- to post-test (P < 0.05). **Significant difference in pre- to post-test change between groups (P < 0.05).*

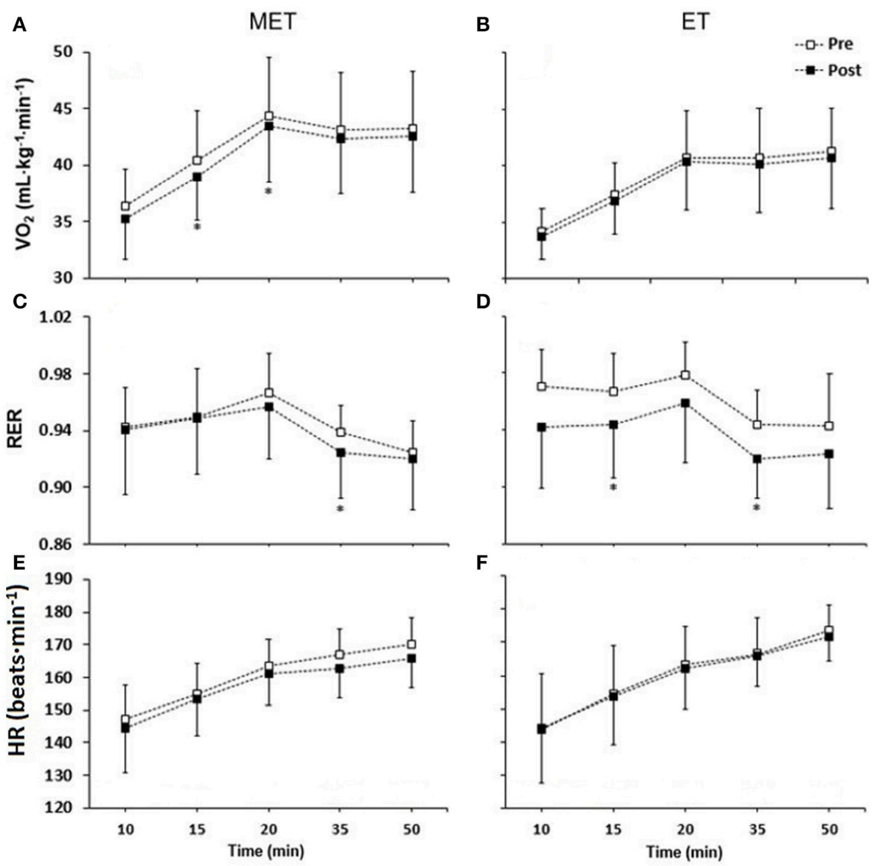

FIGURE 6 | O2-cost; VO_2 **(A,B)**, respiratory exchange ratio, RER **(C,D)** and heart rate, HR **(E,F)** during the prolonged 50-min double poling protocol before (pre-test) and after (post-test) the 6-week intervention period. MET, Combined endurance training and muscular endurance training (left), ET, endurance training (right). Data are expressed as group mean ± standard deviation. *Different from pre-test ($P < 0.05$).

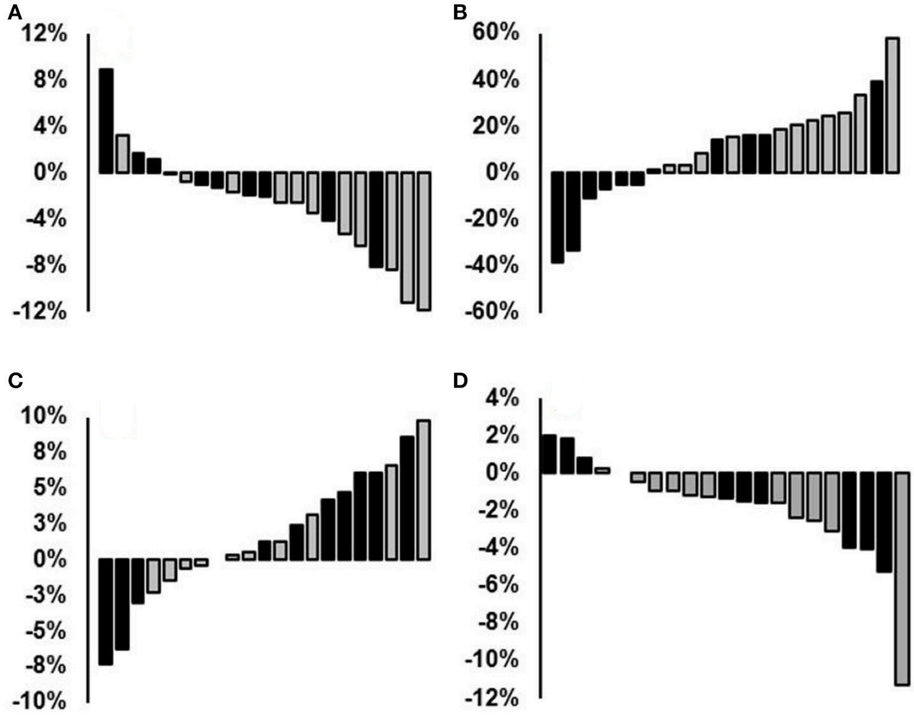

FIGURE 7 | Percent individual changes from pre- to post-test: **(A)** 1,000-m time, **(B)** muscular endurance, **(C)** VO_{2peak} double poling ($mL \cdot kg^{-1} \cdot min^{-1}$) and **(D)** average O_2-cost from the following measuring intervals: 8 to 10, 13 to 15, 18 to 20, 33 to 35, and 48 to 50 min. MET, Combined endurance training and muscular endurance training (gray columns); ET, endurance training (black columns).

possible training benefits of increased upper-body training in XC skiers (Sandbakk and Holmberg, 2017). However, there is very little information on which type of training is most effective in stimulating these adaptations, and future studies should examine possible mechanisms more in detail. Interestingly, both groups displayed the same VO_{2max} in running after the training intervention despite MET replaced half of the high-intensity interval sets with upper-body muscular endurance training. This may be important information regard tapering strategies where reduction in volume, while maintaining intensity and training frequency, have been proposed to induce an "optimal" strategy in the final weeks before competition (Bosquet et al., 2007).

The relative increase in muscular endurance per session (~1.8%) is larger than previous reported in comparable studies on specific upper-body training (0.7–1.1%) (Stone and Coulter, 1994; Schoenfeld et al., 2015). However, Schoenfeld et al. (2015) and Stone and Coulter (1994) included 24 and 27 training sessions respectively, compared to 12 in the current study. It is therefore possible that athletes could gain a relative large increase in muscular endurance within a few sessions. This notion is particularly interesting from a "block periodization" perspective, herein shorter training periods (1–4 weeks) are utilized to focus on improving a few selected abilities (Issurin, 2010). Moreover, even though the aim of the training was to increase muscular endurance, strength gain (1RM) per session in the current study was similar to studies in heavy strength training for XC skiers (0.6 vs. 0.5–1.2% per session; Losnegard et al., 2011; Rønnestad et al., 2012; Skattebo et al., 2015). This implies that low resistance strength training could be an alternative training method to heavy strength training, at least for short-term adaptations prior to competitions or during short block periodization.

Methodological Considerations

We counter-balanced the two groups based on 1,000-m time, VO_{2max} running, 1RM and gender at pre-test. No significant differences between groups were found in training volume in any of the training categories. However, since the subjects were well-trained and not elite athletes, the range between subjects was large in most categories, causing substantial variation in- and between groups. The absolute difference in total training volume of 132 min/week [485 min (MET) vs. 353 min (ET)] prior to the intervention period was mainly caused by a 107 min difference in weekly DP training on rollerski. This can indicate that MET had less potential for physiological adaptation than ET, which strengthens findings of the improved 1,000-m. On the other hand, MET reduced weekly DP training by 50 min (−27%) from pre-intervention compared to the intervention period, and a reduction in training volume is related to tapering and potentially improved performance (Bosquet et al., 2007; Mujika, 2010). Altogether, using recreational but well-trained skiers with large variations in training load may potentially be a limitation in the present study and should therefore be taken into consideration when interpreting the results. Another aspect is that HIT was replaced with muscular endurance, and not that training was added to their normal training, as done in most other studies. This was based on the fact that recreational athletes normally have limited time to execute training (e.g., full time work) and thereby relative low training volume compared to elite athletes. Hence, adding training in one group would lead to an increase in total volume, which could lead to a greater training stimuli it selves, and potentially enhanced performance. Finally, one strengthen of the present study is the applied perspective with direct practical application for coaches and athletes that aim on optimizing performance. However, one clear limitation of the study is the lacking methodology to analyse possible changes in intrinsic factors (such as muscle fiber types, mitochondria, capillary density and neuromuscular characteristics). Hence, since this was out of the scope of the present study, further studies should investigate the potential adaptations more in detail.

CONCLUSION

Six weeks of upper-body muscular endurance training increased muscular endurance and maximal strength in a simulated DP exercise and improved DP performance following 50 min submaximal trial. Finally, replacing half of the running interval sets with upper-body muscular endurance training had no negative effects on the skiers' VO_{2peak} in DP or VO_{2max} running.

ETHICS STATEMENTS

This study was carried out in accordance with the recommendations of Regional Committee for Medical and Health Research Ethics, Norwegian Research Ethics Act (2006) and Act on Medical and Health Research (2008) with written informed consent from all subjects. The study was conducted according to the Declaration of Helsinki and Norwegian law.

AUTHOR CONTRIBUTIONS

We hereby state that the contributions from the authors are in line with author guidelines as described below. The conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; JB, SNJ, BR, and TL Drafting the work or revising it critically for important intellectual content; JB, SNJ, BR, and TL Final approval of the version to be published; JB, SNJ, BR, and TL Questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; JB, SNJ, BR, and TL.

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Sedentary Behavior among National Elite Rowers during Off-Training—A Pilot Study

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The aim of this pilot study was to analyze the off-training physical activity (PA) profile in national elite German U23 rowers during 31 days of their preparation period. The hours spent in each PA category (i.e., sedentary: $<$1.5 metabolic equivalents (MET); light physical activity: 1.5–3 MET; moderate physical activity: 3–6 MET and vigorous intense physical activity: $>$6 MET) were calculated for every valid day (i.e., $>$480 min of wear time). The off-training PA during 21 weekdays and 10 weekend days of the final 11-week preparation period was assessed by the wrist-worn multisensory device Microsoft Band II (MSBII). A total of 11 rowers provided valid data (i.e., $>$480 min/day) for 11.6 week days and 4.8 weekend days during the 31 days observation period. The average sedentary time was 11.63 ± 1.25 h per day during the week and 12.49 ± 1.10 h per day on the weekend, with a tendency to be higher on the weekend compared to weekdays ($p = 0.06$; $d = 0.73$). The average time in light, moderate and vigorous PA during the weekdays was 1.27 ± 1.15, 0.76 ± 0.37, 0.51 ± 0.44 h per day, and 0.67 ± 0.43, 0.59 ± 0.37, 0.53 ± 0.32 h per weekend day. Light physical activity was higher during weekdays compared to the weekend ($p = 0.04$; $d = 0.69$). Based on our pilot study of 11 national elite rowers we conclude that rowers display a considerable sedentary off-training behavior of more than 11.5 h/day.

Keywords: accelerometer, microsoft band 2, multi-sensor, recovery, sedentary behavior, wearable

INTRODUCTION

Elite rowers invest a considerable amount of time for their training averaging >1,000 h per year (Fiskerstrand and Seiler, 2004) i.e., approximately 17% of h per year of waking time. Nevertheless, a great proportion of available time is not spent for training but for recovery including activities of daily living, such as studying, working, traveling etc.

Past investigations focused on analyzing and optimizing the quality of training (Fiskerstrand and Seiler, 2004; Stoggl and Sperlich, 2015), however very little is known about the intensity and volume of physical activity (PA) performed by elite athletes during their off-training time which, as mentioned above, accounts for more than 80% of waking time. This is astonishing as we know that the rate of adaptation (although not exclusively) is an integral of the training stimulus itself (intensity, duration and frequency of stimulus), environmental surrounding, behavior (e.g., nutrition) but also the type of (acute) recovery strategies (Bishop et al., 2008). Largely, this "integrative dose" determines one's individual biological adaptation as well as health.

Surprisingly, to the best of our knowledge only one study so far investigated the PA of elite athletes outside their sport-activity (Weiler et al., 2015) concluding that the elite soccer players were surprisingly sedentary during off-training, especially when compared to non-athletic groups. In this context, recent studies also showed increased prevalence of overweight and obese athletes indicating increased sedentary behavior (Nikolaidis, 2012, 2013). Sedentary behavior as such is defined as any waking behavior characterized by an energy expenditure $\leq$1.5 metabolic equivalents (MET), while in a sitting, reclining or lying posture (Tremblay et al., 2017). Evidence exists that elevated levels of sedentary behavior in the non-athletic population are associated with various adverse health outcomes, such as cardiovascular disease, diabetes, and all-cause mortality (Chau et al., 2013; de Rezende et al., 2014).

Within the athletic population it is accepted that active when compared to passive (i.e., inactive) recovery (after high-intensity efforts) (Riganas et al., 2015) is likely to impact overall recovery and sport performance (Laursen and Jenkins, 2002; Buchheit et al., 2009). In elite rowers e.g., active compared to passive recovery provides higher rate of lactate removal compared to passive recovery (Riganas et al., 2015) and the active recovery with a more rapid regulation of homeostasis (although not fully understood) may regulate growth and transcription factors (Coffey and Hawley, 2007). In this context, sedentary off-training behavior may negatively affect recovery and in a long-term adaptation to exercise and health.

In summary, analysis of sedentariness in the elite athletic population is rare and only assessed in a team sport setting and not among elite endurance athletes. Potential identification of sedentariness could (i) lead to a change in the view of off-training procedures (e.g., active recovery) and (ii) could stimulate health advice in light of reducing the risk of sedentary-induced all-cause negative health effects due to accustomed in-career sedentary behavior. Therefore, this pilot study aimed to analyse the off-training PA profile in national elite German U23 rowers during 31 days of their preparation period. Based on a previous analysis in football (Weiler et al., 2015) we hypothesized that elite rowers display a considerable sedentary off-training behavior.

METHODS

Participants

Eleven German U23 rowers, competing at national or international level took part in this investigation (peak oxygen uptake: 66 ± 5 mL·min^{-1}·kg^{-1}, 20 ± 2 years, body mass: 88.4 ± 9.7 kg, height: 189 ± 7 cm). The inclusion criteria were: (i) age 18–30 years; (ii) male; (iii) squad member of either regional or national level with seamless periods of rowing before study initiation. Exclusion criteria were: (i) medically unfit to perform the study according to previous recommendations (Steinacker et al., 2002). All participants gave their written informed consent to participate in the study which was conducted in accordance with the Declaration of Helsinki. All protocols were pre-approved by the ethical review board of the University of Ulm.

Assessment of Physical Activity (PA)

Data collection took place during the final 11-week preparation period (i.e., calendar week 3–14) before the rowers' first competition of the season. Each rower was instructed to wear a wrist-worn multisensory device Microsoft Band II (MSBII), for a period of 1 month (31 days, with 21 weekdays, and 10 weekend days) only removing it for scheduled training sessions and showering. The MSBII incorporates several sensors including a 3-axis accelerometer, gyrometer, optical heart-rate sensor, galvanic skin response sensor, ambient light sensor, ultraviolet light exposure, and skin temperature sensor. The MSB2 stores the data of mean hourly energy expenditure online.

Preliminary Analysis

Beforehand we validated the measurement of energy expenditure of the multi-sensory MSBII with the energy expenditure from indirect calorimetry (Metamax 3B, Cortex, Leipzig, Germany) in nine physical education students. Depending on their level of performance they sat, stood, walked at 3, 4, 5 km·h^{-1} or jogged at 7.2, 9.0, 10.8, and 12.6 km·h^{-1} for 3-min. During each 3-min activity the energy expenditure was measured with the MSBII and a previously validated (Medbo et al., 2002) breath-by-breath metabolic cart (MetaMax 3B, Cortex Biophysik, Leipzig, Germany). In accordance with the manufacturer's instructions both, the gas and flow sensor were calibrated prior to all testing.

Over the activity range from 1 to 10 MET (**Figure 1**), i.e., sitting, standing, walking, and jogging the Pearson correlation coefficient (r) calculation revealed a significant and nearly perfect correlation between the energy expenditure calculated from the multi-sensory MSBII and the energy expenditure from indirect calorimetry ($r = 0.92$; $r^2 = 0.84$, $p < 0.001$).

The correlation coefficients of this preliminary testing are even higher than previously published correlation coefficients when comparing the energy expenditure assessed by multi-sensor devices and indirect calorimetry in healthy adults [*r* ranging from 0.56 (Fruin and Rankin, 2004) to 0.85 (Dwyer et al., 2009)].

To classify energy expenditure in established PA classifications (Ainsworth et al., 2011; Sedentary Behaviour Research Network, 2012) we normalized the energy expenditure by individual body mass and categorized received mean METs/hour as sedentary activity (<1.5 MET), light (1.5–3 MET), moderate (3–6 MET), and vigorous intense PA (>6 MET). Non-wear time was identified by checking heart rate data, i.e., if no valid heart rate was present for an hour it was deemed that the device must have been removed in that hour. According to the manufacturer, the MSBII automatically tracks the duration of sleep integrating biometric data of heart rate and motion or when the athlete personally activates the sleeping mode. The hours spent in each PA category were calculated for every valid day of data recorded, where a valid day consists of at least 480 min of wear time during waking hours of the non-training period in correspondence with

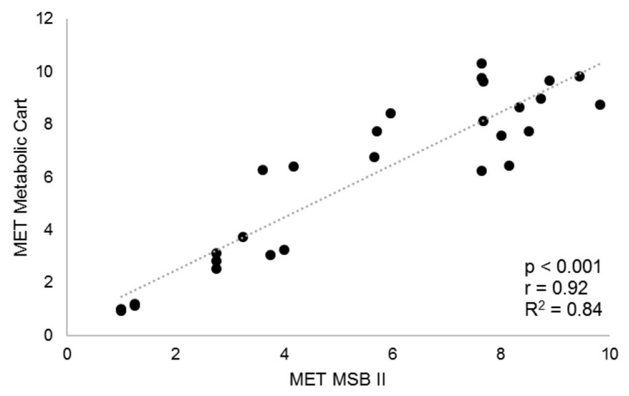

FIGURE 1 | Correlation analysis of energy expenditure measured by MSBII and indirect calorimetry (Cortex Metamax 3B) of nine subjects sitting, standing, walking and jogging.

TABLE 1 | Summary of daily activity of 11 rowers during their preparation period.

		Mean ± SD	95% CI	*P*; *d*
Valid days	Weekday	11.55 ± 4.25	8.69–14.40	<0.001*
	Weekend	4.81 ± 1.53	3.79–5.85	2.11
Mean wear time per day [h]	Weekday	22.31 ± 1.14	21.54–23.08	0.67
	Weekend	22.05 ± 1.51	21.04–23.07	0.19
Sedentary time (<1.5 MET) in waking hours [h]	Weekday	11.63 ± 1.25	10.80–12.48	0.06
	Weekend	12.49 ± 1.10	11.77–13.21	0.73
Light PA (1.5–3 MET) [h]	Weekday	1.27 ± 1.15	0.49–2.05	0.04
	Weekend	0.67 ± 0.43	0.37–0.96	0.69
Moderate PA (3–6 MET) [h]	Weekday	0.76 ± 0.37	0.51–1.00	0.13
	Weekend	0.59 ± 0.37	0.31–0.87	0.45
Vigorous PA (>6 MET) [h]	Weekday	0.51 ± 0.44	0.20–0.83	0.97
	Weekday	0.53 ± 0.32	0.25–0.80	0.05
Sleep time [h]	Weekday	8.18 ± 1.24	7.35–9.01	0.80
	Weekend	8.07 ± 1.34	7.17–8.97	0.08

*PA, Physical activity; d, Cohen's d effect sizes calculated from the Mean ± SD between weekdays and weekend; *Indicates differences between weekdays and weekend for P < 0.05.*

(Atkin et al., 2012). Data classified as time in bed and invalid days (<480 min of wear time) were excluded from the analyses.

Statistical Analysis

The data to calculate the MET values were processed using the Python data analysis toolkit "pandas" (0.18.0) and the scientific computing library "SciPy" (0.17.0) available for the Python programming language (3.5.1). Further analysis was conducted using the Statistica software package for Windows® (version 7.1, StatSoft Inc., Tulsa, OK, USA). That is, a student's paired *t*-test was employed to calculate the differences between weekdays and weekend activities [i.e., sedentary time (<1.5 MET); light PA (1.5–3 MET), moderate PA (3–6 MET); vigorous PA (>6 MET)]. An alpha of $p < 0.05$ was considered as significant. The effect size, Cohen's *d*, (Cohen, 1988) was calculated for all variables, with the thresholds for small, moderate, and large effects set at 0.20, 0.50, and 0.80, respectively (Cohen, 1988). Medium or large effects sizes were considered as tendencies if comparisons based on *p*-values were insignificant.

RESULTS

A total of 11 rowers provided valid data (i.e., >480 min/day) for 11.6 week days and 4.8 weekend days during the 31-day observation period.

All mean data for sedentary time, light, moderate and vigorous PA as well as sleep are summarized in **Table 1** and the corresponding fraction of total wear time during off-training periods are illustrated in **Figure 2**.

The average sedentary time was 11.63 ± 1.25 h per day during the week and 12.49 ± 1.10 h per day on the weekend, with moderate effect sizes indicating sedentary time to be higher on the weekend ($p = 0.06$; $d = 0.73$). The average time per day in light, moderate and vigorous PA during the weekdays was 1.27 ± 1.15, 0.76 ± 0.37, 0.51 ± 0.44 h per day, and 0.67 ± 0.43, 0.59 ± 0.37, 0.53 ± 0.32 h per weekend day. Light activity was higher during weekdays compared to weekend ($p = 0.04$; $d = 0.69$).

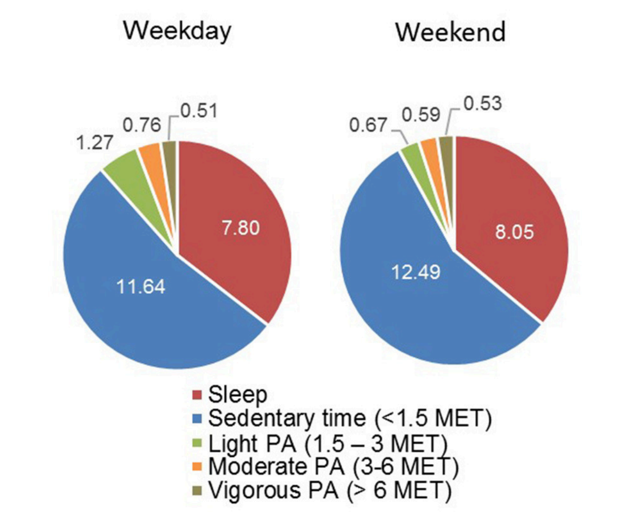

FIGURE 2 | Fraction of mean sedentary time [hours], light, moderate, and vigorous PA as well as sleep of total wear time during off-training periods.

DISCUSSION

In the present study, we aimed to analyze the off-training PA of national elite U23 rowers during their preparation period. To the best of our knowledge this is the first investigation among endurance athletes.

The main findings of this investigation were that national elite U23 rowers when compared to non-athletic population studies (Schuna et al., 2013; Owen et al., 2014) display a larger proportion of time sedentary (<1.5 MET), a lower proportion of light PA, but at the same time display a greater amount of moderate to vigorous PA (>3 MET) in addition to their often vigorous training activity. In their secondary analyses of the NHANES from 2005 to 2006, Schuna and co-workers present a mean sedentary time of 478.9 (2.6) min/day, 200.0 (1.5) min/day in low PA, 141.3 (1.8) min/day in light PA, 87.8 (1.2) in lifestyle PA, and 22.8 (0.7) min/day in moderate-to-vigorous intensity PA (Schuna et al., 2013).

The rowers in the present study spent >11.5 h sedentary i.e., expending a mean metabolic equivalent of <1.5 METs per hour which corresponds to sitting, lying and passive transportation etc. The present data is in line with a previous investigation (Weiler et al., 2015) analyzing professional footballers during an English league season and demonstrating significant sedentary behavior among elite footballers. In the latter study, the footballers spent approximately 8 ± 1 h of waking time sedentary. In the present study, the rowers were about 3.5 h more sedentary (hours per day spend at <1.5 METs) during the weekdays and 4.5 h more sedentary during the weekend. One reason for the calculated sedentariness of our rowers may be attributable to the algorithm (hourly average of activity) of the MSBII neglecting short interruptions of sedentary time with activities of more than 1.5 MET.

However, it is important to note that the sedentariness in our rowers was higher during the weekend compared to weekdays, which has also been confirmed as pattern in other non-athletic populations, such as students (Clemente et al., 2016). Since the rowers were not professional athletes they might not have had enough time (due to work, education, etc.) during the week to perform longer and/or (very) intense sessions. Longer session (and maybe more intense sessions) would lead to fatigue resulting in less off-training activity.

However, the rowers in the present study spent clearly more time (2 min vs. 30 min) at vigorous activity (>6 MET) when compared to elite footballers (Weiler et al., 2015). We can only speculate to why rowers display more vigorous activity during their off-training but maybe this mirrors, at least in part, the typical behavior of rowers preferring more vigorous and exhausting exercise. However, we cannot exclude that some rowers added additional non-scheduled exercise into their free time e.g., a soccer game.

Active vs. Sedentary Recovery

To improve recovery, various responses of different modalities have been investigated including macronutrient supplementation (McLellan et al., 2014), massage techniques (Poppendieck et al., 2016), cooling (Poppendieck et al., 2013), self-myofascial release (Beardsley and Skarabot, 2015), neuromuscular electrical stimulation (Babault et al., 2011), active vs. passive recovery (Laursen and Jenkins, 2002; Buchheit et al., 2009; Riganas et al., 2015) (and many more), all of which are performed rather temporarily (minutes to maybe 1 h) and employed promptly after exercise. Short-term active compared to passive recovery in rowers is known to provide a higher rate of lactate removal compared to passive recovery (Riganas et al., 2015) and active recovery with a more rapid regulation of homeostasis (although not fully understood) may regulate growth and transcription factors (Coffey and Hawley, 2007). Similarly, lactic acid clearance measured 20 min after repeated supramaximal leg exercise (i.e., Wingate tests) is significantly greater with active compared to passive recovery and massage in cyclists (Martin et al., 1998). Likewise, young elite futsal players perceive more benefit from immediate postgame (water) exercises compared to dry exercises and seated rest, which is thought to improve their attitude toward playing (Tessitore et al., 2008). In contrast, results indicate that passive and active (i.e., running 5 miles on a flat course on two consecutive days, at an intensity of 65–75% of maximum heart rate) recovery result in similar mean 5-km performance (Bosak et al., 2008). Equally, a single 30-min session of aqua cycling was not able to attenuate the effects on muscular performance, markers of muscle damage, or delayed onset of muscle soreness (DOMS) compared with passive rest (Wahl et al., 2017).

Finally, muscle activation induces blood flow (Sperlich et al., 2013), thereby delivering oxygen and substrates to the muscle and also supports the clearances of metabolites. So, from this perspective, any form of (light) muscle activity during off-training should support circulatory induced recovery.

Based on our experience, active recovery is employed immediately or with time-delay after exercise and for a certain (short) period of time. Since an extremely high variability of "best" recovery scheme exists between different athletes (Bishop et al., 2008) it is astonishing, that no study so far (at least to the best of our knowledge) has investigated the influence of different (long-term) off-training PA profiles in athletes. We acknowledge the fact that certain "sedentary behavior" maybe necessary for elite athletes to properly recover, however the impact of prolonged sedentary behavior during off-training and its impact on athletic recovery, performance or injury risk is unknown. From this perspective, future investigation may aim to answer the question whether the manipulation of off-training PA may be beneficial or harmful for recovery processes and long-term performance development in elite athletes.

Health Risk of Sedentariness in Athletes?

Although it is well-known that sedentary behavior is related to all-cause mortality (Chau et al., 2013; de Rezende et al., 2014) elite athletes may not be increasingly threatened by this risk (Ekelund et al., 2016). However, Olympic athletes are not immune toward cardio-vascular disorders and might be exposed to unexpected high-risk of cardiovascular abnormalities during sport activity (Pelliccia et al., 2017). Additionally, there is some evidence indicating that elite endurance athletes, when retired, change their body composition more than aerobic characteristics with age (Mujika, 2012). From this perspective, the sedentary behavior of active athletes may not directly be harmful to their health but, especially after retiring from their sporting career, these individuals may be at high risk of sedentary-induced all-cause mortality due to accustomed in-career sedentary behavior.

There is some evidence that interrupting sitting time every 20–30 min by standing up or walking helps to counteract cardio-metabolic disease (Dunstan et al., 2012) and bodies, such as the American College of Sports Medicine address the issue of reducing sedentary behavior (Kravitz and Vella, 2016) repeatedly. The athletic population may not feel addressed, because of their high training related PA. In all cases, athletes should be informed about their current off-training PA profile and the long-term risk associated with sedentary behavior. In this context commercially available wearable sensors (Duking et al., 2016), as long as they fulfill scientific quality criteria (Sperlich and Holmberg, 2017), and do not danger personal data security (Austen, 2015), may be useful in providing feedback (Duking et al., 2017) of daily PA patterns.

Methodological Considerations

Some methodological considerations need acknowledgment: First, we only observed a short period within the season of competitive rowers, i.e., 31 days. Although, this observation period is significantly longer compared to other studies investigating PA patterns (Schuna et al., 2013) we cannot judge whether the PA profile during off- and competition season would be different. Secondly, since our rowers were among the best athletes in Germany we cannot estimate whether the result is also true for recreational, female, youth or older rowers. Thirdly, the data analysis of the MSBII does not allow to record PA densely, i.e., data every second or minute within a 24-h cycle. Consequently, we could not assess the quantity of possible micro bouts of PA, which might have been leveled off through sedentary behavior for the rest of the hour. Also, the position of the wrist-worn device could have an error in the calculation of energy expenditure. Although we instructed all rowers to wear the MSBII always on the same arm we cannot be sure if this was the case all the time.

Also, from a methodological point of view, the number of rowers in the present pilot study was relatively small and more participants would have allowed greater statistical power. However, the 11 rowers were among the best of their age group in Germany and increasing the sample size would have meant to integrate "weaker" rowers thereby confounding the interpretation of the data for the "elite" rowing population. As this study was designed as pilot study, further research is warranted and the present results should be viewed carefully until the data is confirmed in other populations.

Practical Consideration

As mentioned previously (Sperlich and Holmberg, 2017), wearable technology allows to collect as much information as possible to be obtained by continuous 24-h monitoring of various PA and also estimate sleep, and various environmental conditions. As long as scientific quality is ensured (Duking et al., 2016; Sperlich and Holmberg, 2017) and personal data secured, such technology can potentially provide a 24-h feedback (Duking et al., 2017) to the athlete and supporting staff about PA during off-training. Individual feedback to PA may assist to counteract exaggerated sedentariness and could stimulate health advice in light of reducing the risk of sedentary-induced negative health outcomes due to accustomed in-career sedentary behavior.

CONCLUSION

Based on our data we conclude that well-trained rowers when compared to other populations display a larger proportion of time sedentary (<1.5 MET) but at the same time display a greater amount of time in moderate to vigorous PA (>3 MET). Future investigation may aim to answer the question whether the manipulation of off-training PA may be beneficial or harmful for recovery processes and long-term performance development and health in elite athletes.

AUTHOR CONTRIBUTIONS

All designed and approved the methods, analyzed data, and assisted in manuscript writing. BS, MB, BWS, KW, and GT performed data collection.

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OPINION
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The Responses of Elite Athletes to Exercise: An All-Day, 24-h Integrative View Is Required!

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The current research topics in Frontiers of Physiology include "Training intensity, volume and recovery distribution among elite and recreational endurance athletes" (Frontiers in Physiology, 2016) and "Wearable Sensor Technology for Monitoring Training Load and Health in the Athletic Population" (Frontiers in Physiology, 2017). As editors of both of these topics, we would like to share some thoughts concerning (a) how they are fundamentally linked and (b) why we believe it is essential to have an all-day, 24-h integrative view to understand elite athletes' responses to exercise.

Athletes who train frequently each week schedule their training and off-training for days (i.e., microcycles, for example, tapering periods, blocks of training) to as long as months (i.e., macrocycles, for example, periods of preparation with different focuses or training camps) to ensure progressive adaptation and prevent fatigue, boredom, and injury. From this perspective, a fundamental goal is to distribute exercise and off-training effectively over a certain period of time (for example, one or several seasons) to achieve optimal adaptation.

Here, we highlight the importance of an all-day, 24-h integrative perspective on training, emphasizing the fact that conditions outside training significantly modulate adaptation, thereby complicating analysis of the distribution of training intensity.

Elite athletes invest a significant amount of time per year in their training, which in some sports amounts to approximately 17% of their waking time (Fiskerstrand and Seiler, 2004). This means that the remaining 83% is spent on activities such as recovery, including for example, massage, physiotherapy, medical treatments, eating, as well as activities of daily living (including sitting, lying, working, studying, active, and passive transportation) and social engagements (for example, media, sponsor, and family activities). All of these activities modulate psycho-biological responses to training.

The various approaches for improving recovery include massage (Poppendieck et al., 2016), cooling (Poppendieck et al., 2013), stretching and self-myofascial release (Beardsley and Skarabot, 2015), neuromuscular electrical stimulation (Babault et al., 2011), compression attire (Born et al., 2013), active recovery (Laursen and Jenkins, 2002; Buchheit et al., 2009; Riganas et al., 2015), and many more, and most of these modalities are performed for relatively short periods of time (from minutes to perhaps 1–2 h or longer) and usually soon after training. Most of these are designed to improve the delivery of oxygen and substrates to muscles and the clearance of metabolites, thereby attenuating or delaying the onset of muscle soreness and rapidly restoring homeostasis, through regulation of growth and transcription factors (Coffey and Hawley, 2007). Clearly, recovery must be taken into account when evaluating the different responses of elite athletes to exercise.

Since moderate-to-light activity (for example, walking or cycling) enhances muscle blood flow, it is surprising that we can find no studies on the influence of physical activity off-training on the biological and psychological outcomes of exercise, especially since the athletic population is alarmingly sedentary when not training (Weiler et al., 2015).

In addition, other factors such as sleep (Nedelec et al., 2015; Gupta et al., 2017) and nutrition (Thomas et al., 2016) are both influenced by the stress of training and, in turn, modulate the response to training in a significant fashion. In addition, drug abuse by and/or frequent medication of athletes may result in epigenic changes and consequently influence physiological adaptation (Kanherkar et al., 2014). It seems imperative that such factors also be taken into account when comparing different approaches to training.

The busy schedules of (elite) athletes involve a relatively high level of psycho-biological stress, due for example, to frequent traveling for short and long distances, often across time zones (Kölling et al., 2016; Fowler et al., 2017), which detracts from preparedness for subsequent training and competition. More understanding is required here as well.

Moreover, environmental factors, such as exposure to an elevated (Sperlich et al., 2017) or lowered level of oxygen (Girard et al., 2017), variations in temperature (Lorenzo et al., 2010; Kruger et al., 2015), and atmospheric stressors such as ozone, particulate matter (Giles and Koehle, 2014), and ultra-violet radiation, exert an impact on various tissues of the human body and thereby potentially modulate responses to training. Accordingly, such factors should also be considered when judging the responses of elite athletes to exercise.

In addition, psycho-social stress resulting from, for example, media exposure, financial and family concerns, fans, and/or one's own expectations may well influence responses to training.

Thus, it appears virtually impossible to take all of these factors into consideration when studying a homogenous group of elite athletes, not even in a controlled laboratory setting. However, both retro- and prospective analyses on the responses and adaptation to training should provide as much information about such modulators as possible. In this context, we feel that a combination of wearable technology and smartphone-based applications should prove invaluable, since this is the only technology that currently allows as much information as possible to be obtained by continuous 24-h monitoring of, in addition to the internal and external training loads themselves, sleep, traveling, various environmental conditions and psycho-social status. As long as scientific quality is maintained (Duking et al., 2016; Sperlich and Holmberg, 2017) and personal data protected, such technology can potentially provide 24-h feedback (Duking et al., 2017) to the athlete and supporting staff concerning the various psycho-biological responses to training. In this regards, future findings on "Wearable Sensor Technology for Monitoring Training Load and Health in the Athletic Population" (Frontiers in Physiology, 2017) will hopefully help provide innovative approaches to investigating the "Training intensity, volume and recovery distribution among elite and recreational endurance athletes."

AUTHOR CONTRIBUTIONS

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

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High Intensity Interval Training Leads to Greater Improvements in Acute Heart Rate Recovery and Anaerobic Power as High Volume Low Intensity Training

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The purpose of the current study was to explore if training regimes utilizing diverse training intensity distributions result in different responses on neuromuscular status, anaerobic capacity/power and acute heart rate recovery (HRR) in well-trained endurance athletes.

Methods: Thirty-six male (n = 33) and female (n = 3) runners, cyclists, triathletes and cross-country skiers [peak oxygen uptake: (VO_{2peak}): 61.9 ± 8.0 mL·kg^{-1}·min^{-1}] were randomly assigned to one of three groups (blocked high intensity interval training HIIT; polarized training POL; high volume low intensity oriented control group CG/HVLIT applying no HIIT). A maximal anaerobic running/cycling test (MART/MACT) was performed prior to and following a 9-week training period.

Results: Only the HIIT group achieved improvements in peak power/velocity (+6.4%, $P < 0.001$) and peak lactate ($P = 0.001$) during the MART/MACT, while, unexpectedly, in none of the groups the performance at the established lactate concentrations (4, 6, 10 mmol·L^{-1}) was changed ($P > 0.05$). Acute HRR was improved in HIIT (11.2%, $P = 0.002$) and POL (7.9%, $P = 0.023$) with no change in the HVLIT oriented control group.

Conclusion: Only a training regime that includes a significant amount of HIIT improves the neuromuscular status, anaerobic power and the acute HRR in well-trained endurance athletes. A training regime that followed more a low and moderate intensity oriented model (CG/HVLIT) had no effect on any performance or HRR outcomes.

Keywords: lactate threshold, peak power, maximal anaerobic running test, mart, MACT, training intensity distribution

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INTRODUCTION

Endurance athletes use different training strategies to improve their performance. Although the bulk of training sessions typically are made up of longer and at slower paced session's (Tonnessen et al., 2014), intervals and higher exercise intensity sessions are a necessity for high performance. To implement diverse types of exercise intensities and durations, athletes use various ways of periodization in their training. The type of periodization depends on the sport and the length of the competition season which decides the duration of the training period. The most common ways for periodization is (i) high volume low-intensity training (HVLIT), lactate threshold training (THR), low-volume high-intensity (interval) training (HIIT) and polarized training, a concept consisting of mixing training between low and high intensity (POL) or a gradual decrease in training volume from HVLIT to THR and HIIT in a pyramidal fashion (Stöggl and Sperlich, 2015)

Athletes use various tests for evaluation of the training process to accurately target specific elements that are important for performance. Depending on the sport, different quality's such as cardiovascular, muscular, or metabolic variables are key elements for performance to a various degree. The most common way for endurance athletes to track and overview their daily training is the use of heart rate (HR) monitoring (Achten and Jeukendrup, 2003). One of the most significant cardiovascular enhancements is an increased stroke volume which is associated with a lower exercise HR for a given submaximal work (Blomqvist and Saltin, 1983). Furthermore, HR recovery (HRR) after cessation of exercise has been put forward as a useful indicator to track cardiovascular advances for athletes of various levels (Daanen et al., 2012). As an example, HRR was tracked in well-trained cyclists throughout a training period of 4 weeks constituting 8 × 4 min HIIT two times per week (Lamberts et al., 2009). It was concluded that well-trained athletes, who responded well to this type of training, demonstrated a faster HRR after the interval session and after a 40-km time trial (HR drop during the 60 s post-exercise) that further was related to an enhanced endurance performance. To note, that no other training- or control-group was included in this study. Additionally, HRR relating to both the drop and the time to reach a certain beat per minute, responds differently to various forms of interval training regimes (Buchheit et al., 2008). This indicates that HRR could provide beneficial feedback for cardiovascular adjustments, not only during exercise, but also in between exercise bouts.

Another frequent used tool for determination of physiological response is determination of blood lactate concentration. Most often blood lactate is related to an increase in exercise intensity to identify various lactate thresholds (Beneke et al., 2011). During variable intensity exercise blood lactate recovery has been suggested as a good indicator for performance both for cycling and cross-country skiing (Björklund et al., 2007, 2011). These latter studies were conducted on well-trained athletes. Also, different types of training seem to stimulate the lactate removal abilities as middle distance runners surpass sprint runners regarding lactate recovery in between high intensity bouts (Bret et al., 2003).

Performance tests with intermittent character are a common and valid instrument to explain performance progress that do not relate to aerobic characteristics. For evaluation of the athletes' neuromuscular status and anaerobic power maximal anaerobic treadmill tests are a useful assessment, i.e., MART (Paavolainen et al., 1999b; Nummela et al., 2006). The test is of intermittent character with an increase in exercise intensity for consecutive bouts and is terminated at volitional fatigue. This test relates to the individuals anaerobic input to the exercise performance and could therefore provide an estimate which areas the athletes lack and need to improve for enhanced performance. To note here, that the effects of different endurance training concepts on key components of endurance performance were shown previously (Stöggl and Sperlich, 2014), while the effects of these training concepts on anaerobic power and HRR are lacking.

The aim of the study was to evaluate the effects of different training concepts (POL vs. HIIT vs. HVLIT) with respect to anaerobic power, cardiovascular and metabolic response using key measurements during the MART and HRR. We hypothesized that athletes who use training concepts involving high intensity elements, i.e., HIIT and POL, would display superior improvements compared with athletes that use no HIIT (i.e., HVLIT).

MATERIALS AND METHODS

Participants

Thirty-six competitive endurance athletes (three females and 33 males) who participated in either cross-country skiing, cycling, triathlon, middle- or long-distance running volunteered to take part in this study (mean ± *SD*: age: 31 ± 6 yrs, body mass: 74.6 ± 8.9 kg, height: 180 ± 7 cm) were recruited from regional cycling, running, triathlon, athletic, and cross-country skiing clubs. All participants were well-trained athletes [61.9 ± 8.0 $mL \cdot kg^{-1} \cdot min^{-1}$ (range: 54–75 $mL \cdot kg^{-1} \cdot min^{-1}$)], accustomed to a training frequency of more than five sessions per week (totally 10–20 $h \cdot wk^{-1}$), participated frequently in endurance competitions for the last 8–20 years and were healthy throughout the intervention period. Participants were members or former members of the Austrian cross-country skiing national team ($n = 8$), runners and triathletes ($n = 10$) or cyclists ($n = 13$) of regional sport teams during or since the year before the current study. Retrospective analysis of the 6 months training prior to the study revealed that none of the participants had regularly engaged HIIT. Instead all had used a HVLIT training protocol with a maximum of two THR training sessions per week.

Based on the participants' baseline VO_{2max} and training mode (running or cycling), all athletes were parallelized into three groups: HIIT, POL, and control group (CG; HVLIT oriented with 1–2 THR sessions per week). At baseline, the three groups were not statistically different with regard to age, height, body mass, or VO_{2max}. During an initial visit, study details, and participation requirements were explained, and all participants gave written informed consent. The study and protocol received approval from the University of Salzburg Austria Ethics Committee and was conducted in accordance with the Declaration of Helsinki.

Design

The intervention lasted 9 weeks plus 2 days of pre- and post-testing. All athletes who were mainly engaged in cycling training during the intervention period trained with their own bike and completed all tests on a bicycle ergometer (Ergoline, Ergoselect 100P; Bitz, Germany) using their own cycling shoes and pedal system. Other athletes ran during the study and completed their pre- and post-testing on a motorized treadmill (HP Cosmos, Saturn, Traunstein, Germany). All participants were instructed not to change their diet throughout the training period and to maintain strength training, if it was part of their training program. Participants' nutritional intake was not standardized or controlled during the study, but for the 3 h prior to all testing in which food intake was not permitted. The training intensity was controlled by HR based on the baseline incremental test: (i) low intensity training (LIT, HR at blood lactate value <2 mmol·L^{-1}); (ii) moderate intensity training (MIT, HR corresponding to a blood lactate of 3–5 mmol·L^{-1}); (iii) high intensity interval training (HIIT, $>90\%$ HR_{max})] (e.g., Seiler, 2010; Stöggl and Sperlich, 2015). The HR was measured during each training session and athletes documented training mode, exercise duration and intensity in a diary. As a control and for detailed analysis, HR for all training sessions was stored digitally and analyzed retrospectively. For the quantification of the training intensity distribution within the 9-weeks of training the session goal approach according to Seiler and Kjerland (2006) was applied.

HIIT Intervention

The HIIT included two interval blocks of 16 days with one adaptation week prior to and one recovery week after each block. The adaptation week included two 60 min HIIT sessions, three 90 min LIT sessions, one 120 min LIT session and 1 day of recovery. The condensed 16 day interval block included 12 HIIT sessions within 15 days, integrating four blocks of three HIIT sessions for 3 consecutive days followed by 1 day of recovery. The recovery week contained four LIT sessions of 90 min and 3 days without any training. All of the HIIT sessions included a 20 min warm-up at 75% of HR_{max}, 4 × 4 min at 90–95% of HR_{max} with 3 min active recovery and a 15 min cool-down at 75% HR_{max} based on the protocol proposed earlier (Helgerud et al., 2007). The LIT sessions lasted 90–150 min depending on the training mode (running vs. cycling) at an intensity resulting blood lactate of <2 mmol·L^{-1}.

POL Intervention

The POL included three blocks, each lasting 3 weeks: 2 weeks of high volume and intensity training followed by 1 week of recovery. The high volume and intensity week included six sessions with two 60 min HIIT sessions, two 150–240 min long duration LIT sessions (duration according to training mode: cycling, running or roller skiing), which included six to eight maximal sprints of 5 s separated by at least 20 min, and two 90 min LIT sessions. The recovery week included one 60 min HIIT session, one 120–180 min LIT session and one 90 min LIT session.

Control Group (CG/HVLIT)

The CG continued their HVLIT dominated training regime with a maximum of two THR sessions per week with no HIIT sessions. The control group also had three blocks each lasting 3 weeks with 2 weeks of high-volume training followed by 1 week of recovery.

Pre- and Post-testing

All participants were asked to report well-hydrated and to refrain from consuming alcohol and caffeine for at least 24-h, as well as from engaging in strenuous exercise at least 48-h prior to testing. The pre- and post-tests included a VO_{2max} ramp protocol and a maximal anaerobic running/cycling test (MART/MACT) based on the protocol of Rusko et al. (1993) in running and Tossavainen et al. (1996) in cycling.

On the first test day all athletes completed a VO_{2max} ramp protocol to determine maximal oxygen uptake (VO_{2max}) and maximal HR (HR_{max}). First, the workload for running was set at 8 km·h^{-1} (inclination: 5%) on the treadmill, and for cycling at 200 W with a cadence of >80 rpm for 10 min. The workload was then increased every 30 s by 0.5 km·h^{-1} (inclination: 10%) on the treadmill or 15 W on the cycle ergometer until exhaustion. VO_2 was measured with an open circuit breath-by-breath spirograph (nSpire, Zan 600 USB, Oberthulba, Germany), which was calibrated prior to each test using high precision gas (15.8% O_2, 5% O_2 in N; Praxair, Düsseldorf, Germany) and a 1 L syringe (nSpire, Oberthulba, Germany). All respiratory data were averaged every 30 s.

On the second day athletes performed the MART/MACT. The protocol included stages of 25 s (running) or 30 s (cycling; including 3–5 s acceleration time) with 100 s breaks in between. For the running protocol treadmill speed was increased with 1.4 km·h^{-1} increments starting at 14.7 km·h^{-1} on a grade of 7%. For the cycling protocol the test started at 360 W with increments of 40 W. Maximal performance (V_{max}) in the MART was calculated by linear interpolation using the formula: $V_{max} = V_f + ((t/25)\ 1.4\ \text{km·h}^{-1})$, where V_f was the velocity of the last completed workload (km·h^{-1}), t the duration of the last workload (s) and 1.4 m·s^{-1} the velocity difference (ΔV) between the last two workloads. For the MACT, the formula for maximal power output (P_{max}) was: $P_{max} = P_f + ((t/30) \cdot 40\ \text{W})$, with P_f as the power output of the last completed stage. A 20 µl blood sample from the right earlobe was collected within the 60 s of each 100 s rest period, and in the first, third, fifth and seventh minutes after the end of the last stage into a capillary tube (Eppendorf AG, Hamburg, Germany). All samples were analyzed amperometric-enzymatically (Biosen 5140, EKF-diagnostic GmbH, Magdeburg, Germany) in duplicate, and the mean of the two measures was used for statistical analysis. The lactate sensor was calibrated before each test using a lactate standard sample of 12 mmol·L^{-1}. Results within a range of ± 0.1 mmol·L^{-1} were accepted. Velocity/power output at 4, 6, and 10 mmol·L^{-1} of blood lactate were calculated. HR recovery (HRR) was calculated as the mean value of all delta changes of each stages peak HR (highest value at the end or in the first seconds after the end of the stage) and minimal HR (minimum value during the 100 s break; **Figure 1**).

Statistical Analyses

All data exhibited a Gaussian distribution verified by the Shapiro–Wilk's test and, accordingly, the values are presented as means ± *SD*. Two-way 2 × 3 repeated-measures ANOVA (2 times: pre-post, 3 groups) to test for main effects of time (pre- and post-intervention), group (the three training groups) and the interaction effect between both factors was applied. When a significant main effect over time and/or interaction effect was observed, paired *t*-tests within each group were conducted. Based on the different units of peak velocity/power in the MART/MACT percent changes between pre- to post-values were calculated, and a one-way ANOVA between groups

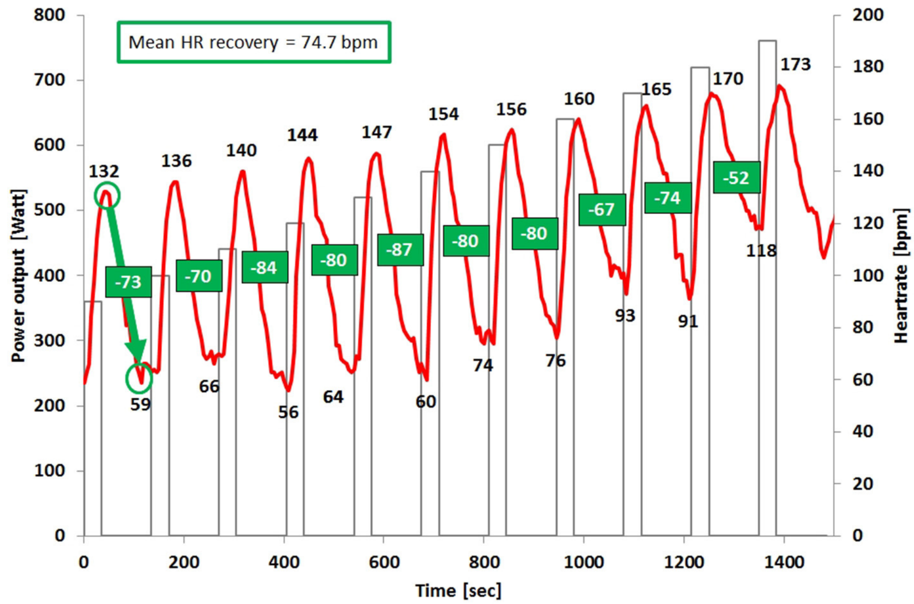

FIGURE 1 | Illustration of the heart rate-time curve and the heart rate recovery calculation within the MART/MACT of one subject.

was performed using Tukey's *post-hoc* analysis. Furthermore, within group changes for these variables were calculated using Wilcoxon tests. In addition, the values obtained were evaluated further by calculating the effect size ($_p\eta^2$). The magnitude of the difference was classified as trivial (<0.01), small (0.01 ≤ to < 0.06), moderate (0.06 ≤ to < 0.14) or large (≥0.14). An alpha value of <0.05 was considered significant. The Statistical Package for the Social Sciences (Version 24.0; SPSS Inc., Chicago, IL, USA) and Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA) were used for statistical analysis.

RESULTS

Thirty-one participants completed the 9-week training protocol, fulfilling more than 95% of the training program and staying within the given HR zones. Seven subjects (2 in HIIT and 4 in CG) withdrew from the study due to illness ($n = 2$) or were excluded due to changes in competition schedule ($n = 2$). The total training hours, number of training sessions and their percent distribution within LIT, MIT, and HIIT are presented in **Table 1**. POL and CG/HVLIT had higher training volume ($P <$ 0.001) and number of trainings session ($P = 0.041$) compared with HIIT. The training intensity distributions with respect to LIT, MIT, and HIIT were 68/6/26% for POL, 43/0/57% for HIIT and 64/35/1% for CG/HVLIT. HIIT demonstrated the lowest number of LIT sessions and CG/HVLIT the highest number of MIT sessions with no difference between the two other groups. HIIT sessions were greatest in HIIT followed by POL and finally CG/HVLIT.

Percent changes in variables from pre- to post-training and between the training concepts during the MART/MACT are presented in **Table 2**. For P/V_{peak} there was a main effect of time and interaction effect time × group (both $P = 0.001$) with HIIT demonstrating the greatest increase (6.4 ± 3.4%, $P < 0.001$) with no significant change in POL (0.2 ± 5.9%, $P = 0.63$) and CG/HVLIT (4.7 ± 5.5%, $P = 0.087$).

For HRR there was a main effect of time ($P < 0.001$) and interaction effect time × group ($P = 0.011$) with HIIT (38.7 ± 10.7 to 49.9 ± 14.1 bpm, 11.2%, $P = 0.002$) and POL (48.9 ± 15.9 to 56.8 ± 22.0 bpm, 7.9%, $P = 0.023$) demonstrating greater increases compared with unchanged levels of 0.1% in CG/HVLIT (49.3 ± 7.5 to 49.4 ± 9.3 bpm, $P > 0.05$) (**Figure 2**). All significant main and interaction effects demonstrated large effect sizes (>0.14).

LA_{peak} demonstrated a time × group interaction effect ($P =$ 0.027) with a 7.3% ($P = 0.001$) increase in HIIT and non-significantly changed values of −6.6% in POL and +1.3% in CG/HVLIT (both, $P > 0.05$).

No changes from pre to post and no differences between training groups were detected with respect to HR_{peak} and velocity /power at 4, 6, and 10 mmol·L^{-1} blood lactate (all $P > 0.05$).

DISCUSSION

The major findings of the study were that (i) only the HIIT group improved their peak velocity or power output in the MART/MACT, (ii) HRR was faster in the HIIT and POL groups compared with no change in the CG/HVLIT group, (iii) while no training intervention improved the velocity or power output at the established lactate concentrations during the MART/MACT.

Anaerobic Power

One of the major findings of this training study were the enhanced P/V_{peak} for the HIIT group, demonstrating the

TABLE 1 | Volume and intensity training distribution within the 9-weeks training intervention (excluding strength training).

	POL	HIIT	CG/HVLIT	*P*-value
Total hours	104 ± 21	66 ± 1*	93 ± 13	<0.001
Number of sessions	54 ± 7	47 ± 1§	54 ± 8	=0.041
Number of LIT training sessions	37 ± 9	20 ± 1*	36 ± 15	=0.004
Number of MIT training sessions	3 ± 4	0 ± 0	18 ± 9*	<0.001
Number of HIIT training sessions	14 ± 3*	27 ± 1*	0 ± 1*	<0.001
Percent LIT training sessions	68 ± 12%	43 ± 1%*	64 ± 20%	=0.002
Percent MIT training sessions	6 ± 7%	0 ± 0%	35 ± 21%*	<0.001
Percent HIIT training sessions	26 ± 7%*	57 ± 1%*	1 ± 1%*	<0.001

*The values presented are means ± SD. P-values were obtained by one-way ANOVA (3 training groups). POL, polarized training group; HIIT, High intensity interval training group; CG /HVLIT, control group with mainly high volume low intensity training; LIT, low intensity training; MIT, moderate intensity training; HIIT, high intensity interval training. *Different from all other groups. §Different from training group "CG/HVLIT."*

greatest increase (+6.4%), with no notable change in POL and CG/HVLIT. Earlier data using cross-sectional comparisons between different types of athletes in running (Nummela et al., 1996) or cross-country skiing (Stöggl and Müller, 2009) showed that P/V_{max} of the MART was determined by metabolic variables as peak lactate and power output or velocity at 10 $mmol \cdot L^{-1}$. The importance of these variables and especially the velocity at 10 $mmol \cdot L^{-1}$ have further been strengthened by the same research group (Nummela et al., 2007). While this cross-sectional data showed important features for anaerobic power reflected in the MART, there was no quantification of the athletes training that preceded the test. In the current study, the HIIT group was the exclusive training modality that had a positive effect on the MART/MACT performance. Indeed, the peak lactate and P/V_{peak} was increased in the HIIT group while it remained unchanged in the other two groups (POL and CG/HVLIT). Certainly, a greater glycolytic activity, which involves formation of lactate, is favorable to produce ATP at a higher rate and likewise should add to the overall performance in the MART/MACT. Therefore, the HIIT intervention seems to have substantial impact on both the metabolic and neuromuscular components of maximal anaerobic performance.

The relationship between the MART and the maximal anaerobic oxygen deficit (MAOD) as well as the energy contribution during the MART was already investigated by Zagatto et al. (2011). Although, the relationship between the MART and MAOD was poor, the quantification of the energetic contribution demonstrated that the aerobic input covers the greatest amount of energy production during the full test, i.e., including both the work and rest periods (65%), while the anaerobic glycolytic energy system contributed with approximately only 5%. When analyzing only the effort periods (25 s) the anaerobic contribution corresponded to ∼74% with the main energy system being the a-lactic (63%) and not the glycolytic lactic system (11%). Moreover, it has been shown that the aerobic contribution increases already at the second repeated bout in sprint exercise (Bogdanis et al., 1996). Therefore, the relation to peak lactate concentration and performance in the MART/MACT within the current study seems conflicting.

TABLE 2 | Per cent changes in velocity (V) and power (P) and at various lactate thresholds as well as peak velocity and power.

	POL	HIIT	CG/HVLIT	*P*-value, Effect size $_p\eta^2$
V/P 4 (%)	−1.6 ± 13.1	4.1 ± 9.6	3.2 ± 13.04	NS, 0.03
V/P 6 (%)	3.3 ± 13.8	1.8 ± 6.5	1.1 ± 8.3	NS, 0.03
V/P 10 (%)	2.8 ± 9.6	0.1 ± 5.5	2.7 ± 7.5	NS, 0.03
V/P_{peak} (%)	0.2 ± 5.9†	6.4 ± 3.4***	4.7 ± 5.5	=0.033, 0.22
LA_{peak} (%)	−6.6 ± 13.3†	7.3 ± 4.7***	1.3 ± 12.3	=0.030, 0.22
HR_{peak} (%)	−0.8 ± 3.9	−0.5 ± 2.8	0.0 ± 3.1	NS, 0.01
HRR (%)	7.9 ± 9.7*	11.2 ± 7.7**	0.1 ± 5.6‡	=0.011, 0.28

*The values presented are means ± SD. P-values were obtained by one-way ANOVA (three training groups) calculated over the per cent differences between pre- to post-training (representing the interaction effect time × group). POL, polarized training group; HIIT, High intensity interval training group; CG/HVLIT, control group with focus on high volume training; V/P4 $mmol \cdot L^{-1}$, velocity or power at 4 $mmol \cdot L^{-1}$ blood lactate; V/P6 $mmol \cdot L^{-1}$, velocity or power at 6 $mmol \cdot L^{-1}$ blood lactate; V/P10 $mmol \cdot L^{-1}$, velocity or power at 10 $mmol \cdot L^{-1}$ blood lactate; V/P_{peak}, peak velocity or power in the MART/MACT; LA_{peak}, peak lactate during the test and within the first 7 min after end of the last completed stage; HR_{peak}, peak heart rate value during the MART/MACT; HRR, mean heart rate recovery; *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ significant difference within groups from pre- to post-training. †Significant different from HIIT group. ‡Significant different to both other groups. NS, not significant.*

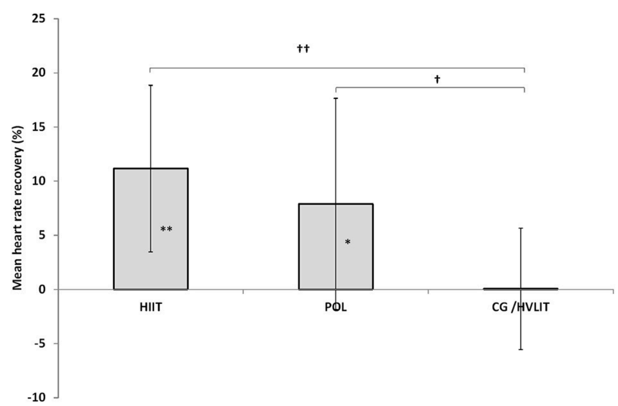

FIGURE 2 | Per cent changes of mean heart rate recovery within the three training groups between pre- and post-intervention testing. *$p < 0.05$, **$p < 0.01$ significant difference within groups from pre- to post-training. †$p < 0.05$, ††$p < 0.01$ significant different to CG/HVLIT group.

The neuromuscular capacity to produce force was shown to be related to both the MART and 5-k running performance (Nummela et al., 2006). Furthermore, close relationships between running performance from distances of 400–5,000 m with performance in the MART and short-duration sprint performance over 20–30 m were found in numerous studies (e.g., Rusko et al., 1993; Nummela et al., 1996, 2006, 2007; Paavolainen et al., 1999a,c). In this context, neuromuscular adaptations using HIIT in ice hockey players, improved the general muscle activation as demonstrated in increased force and rate of force development in an isolated plantar flexion (Kinnunen et al., 2017). Shortcomings in the study of Kinnunen et al. (2017) were the missing transfer of the results to increased sport specific performance (e.g., faster skating times on ice). Compared to the current study, in the study by Kinnunen et al. (2017) a shorter training period (2.5 vs. 9 weeks) and shorter HIIT bouts (30 s vs. 4 min) were applied. The question remains which training period durations using different training regimes (e.g., HIIT protocols) are necessary for these improvements. While these shorter HIIT bouts relate more to team sports as ice hockey, there seem to be also positive effects for sprint triathlon performance where subjects used a mix of short and long bouts (Garcia-Pinillos et al., 2017). In summary, different HIIT regimes have been proven to have a significant impact on trained endurance athletes for endurance performance (Laursen et al., 2002). In all, the improved MART/MACT performance in the current study potentially translates to an improved performance in the athlete's specific sport.

Heart Rate Recovery (HRR)

The two training groups including high intensity sessions, HIIT and POL, displayed a superior HRR during the MART/MACT compared with CG/HVLIT. In detail, HIIT demonstrated the greatest per cent change in HRR (11.2%) followed by POL (7.9%) and no change in CG/HVLIT (0.9%). Conventionally, HRR is measured within the first 60 s after termination of a test or training (Lamberts et al., 2009). In this study, the HRR represents the mean of the acute HRR in between several stages during the MART/MACT. This is the first time that data during the specific MART/MACT has been shown. HRR was found to be different between trained and untrained healthy individuals and that improvements in HRR occur with an increase in training status (Daanen et al., 2012). Also this improved HRR has been used as a reliable test that relates to various performances as longer time-trials as well as peak power output (Lamberts et al., 2011). However, there are conflicting results showing a decreased performance for intermittent high intensity exercise in athletes that show an enhanced HRR (Le Meur et al., 2016). Furthermore, it was suggested that an improved HRR could be biased by a decreased maximal HR. None of the groups in the current study displayed such a pattern as all of them maintained their maximal HR. Even though, it is well-established that the stroke volume increases as a result of endurance training (Blomqvist and Saltin, 1983) the reason for the improved HRR is related rather to the nervous system. A delayed parasympathetic reactivation has been proposed to be part of the HRR post-exercise (Buchheit et al., 2007). Interestingly, the HRR seems to be acutely impaired by a high anaerobic contribution. However, the question is if this is trainable and might be different if the athlete is accustomed to more anaerobic work. Our results indicate that the athletes exposed to HIIT seemed to handle the anaerobic stress better than the HVLIT dominated groups indicated by their superior HRR. Differences in training load can impact HRR (Borresen and Lambert, 2007) as demonstrated by an attenuated HRR following greater training load, defined according to the TRIMP method. In the current study, the HIIT had a markedly lower training load when compared to all other modalities when counting training hours (<70 vs. ∼100 h). Nevertheless, even though the training load was not calculated according to the TRIMP method, the HIIT clearly showed a lower training load based on duration and frequency. Contradictory to our results, regarding training hours, it has been shown that severe increase in training hours per week markedly increases HRR along with a concomitant loss of performance of a single time-trial (Thomson et al., 2016). Notably in our study, the increase in training hours was accompanied with an increase in percent of high intensity exercise which makes it difficult to pin point if it is hours or high intensity exercise that sole alone explain the outcome.

Another aspect for the more pronounced HRR in the groups including high intensity sessions (HIIT and POL) might be the intermittent character of HIIT itself. Possibly, the repeated steady change of high and low intensities within the sessions might be an appropriate stimulus to enhance the ability of the autonomic nervous system to acutely adapt toward changing intensities. Future studies would be of a necessity to cover this area to explore the exact mechanisms.

In all, the training groups that included HIIT (POL and HIIT) both showed an increased HRR. While an enhanced HRR has been interpreted to be part of a functional overreaching with a decreased performance, the short tapering period (days) in the current study has quickly affected the performance in a positive direction. Therefore, the HIIT group likely had sufficient time for recovery in between training sessions to show both improvements in HRR concomitant with performance.

Velocity or Power Output at Absolute Lactate Concentrations

In the current study, neither the velocity nor the power output at any of the established lactate concentrations (4, 6, and 10 $mmol{\cdot}L^{-1}$) showed any improvements. More specific, it is interesting that the CG/HVLIT as the only training group that targeted training at the defined lactate concentration (e.g., approximately two sessions of THR/week) lacked any development in velocity or power output. Interestingly, the lack of improvement is somewhat unexpected as the especially enhanced performance in running is explained by a right shift for lactate threshold in relation to velocity (vLT; Billat et al., 2002). Notably, this change was apparent already after a 4-week intervention.

Another study using HIIT and more traditional training as long slow distance (LSD) displayed increased power outputs for both training modalities at 2 and 4 $mmol{\cdot}L^{-1}$ but with superior development in the HIIT group (Ni Cheilleachair et al., 2017). Their study resembled the adaptation period of the current study as they used an 8-week training intervention. The use of rowers as subjects could likewise be compared to the cross-country skiers in the current study as both sports use whole body work for propulsion. In support of these data a study performed on cyclists comparing HIIT block periodization with a more traditional training regime, i.e., mostly low intensity sessions with a few HIIT sessions (Ronnestad et al., 2014), showed that only the HIIT block periodization increased power output at 2 $mmol{\cdot}L^{-1}$. The training performed was rather similar to the current study using HIIT session of target HR at 88–100% of HR_{max}. The approximately accumulated time at this exercise intensity was 30 min for each occasion in their study. It might be that the stimulus that was used in the current study was too short in duration as it contained 16 min in total per session. However, we used a longer training period that spanned more than twice the weeks (4 vs. 9 weeks). Possibly this could indicate that the amount of time HIIT is performed per session is more important than the accumulated time over a total training period for improvements in velocity or power output at lactate concentrations between 4 and 10 mmol·L^{-1}.

Another aspect that should be mentioned here are the differences in the test protocols when comparing the MART/MACT (25 and 30 s stages with 100 s rest) with a standard incremental protocol (e.g., 3–5 min stages with 20–30 s rest for blood sampling). In this context it is worth noting that in the study of Stöggl and Sperlich (2014) the peak velocity/power at 4 mmol·L^{-1} increased in both POL (+8.1%, $P < 0.01$) and HIIT (+5.6%, $P < 0.05$). Therefore, performance changes at lactate thresholds cannot be directly transferred among different test protocols. This might also be attributed toward the different energy system contributions between the MART/MACT vs. a standard incremental test protocol.

Limitations, Perspectives, and Practical Applications

One limitation of the current study can be seen in the mix between test modalities applied across the participants by using running or cycling tests specific to their preferred training exercise (e.g., cyclist vs. runner). However, because it is not an easy task to recruit large numbers of well-trained to elite athletes for such an experiment, various types of endurance athletes were included. Furthermore, although the MART was shown to be associated with neuromuscular factors/characteristics (Paavolainen et al., 1994, 1999a,c; Nummela et al., 2006) no specific parameters about effects on neuromuscular components were measured in the current study. Therefore, only indirect conclusions from MART performance changes toward neuromuscular components can be drawn.

Future research about long-term effects of different training intensity distributions in well-trained athletes on aerobic and anaerobic key components of performance is warranted. Still the measurement of HRR in between HIIT bouts, or when using the MART for diagnostics as in the current study, could be a practical tool to track physiological adaptations. In addition, the transfer of these enhanced capacities toward real competition situations has still to be proven.

CONCLUSION

In this study of elite athletes performing HIIT, POL, or mainly HVLIT over a period of 9 weeks, only the HIIT group achieved significant improvements (6.4%) in peak performance during the MART/MACT, while, unexpectedly, in no group the performance at the established lactate concentrations (4, 6, 10 mmol·L^{-1}) was changed. Acute HRR was improved only in the HIIT (11.2%) and POL (7.9%) group with no change in the HVLIT oriented control group. Therefore, it might be concluded that only a training regime that includes a significant amount of HIIT improves the neuromuscular characteristics, anaerobic power, and the acute HRR in well-trained endurance athletes. A training regime that followed more a HVLIT oriented model had no effect on any performance outcomes. Practically, if HIIT is incorporated during pre-race preparation, i.e., tapering HRR could provide a useful tool for monitoring adaptions related to anaerobic power and physiological response. These findings shed new light into the cardiovascular, central nervous and anaerobic adaptations in response to training regimes with different training intensity distributions and should be of special interest in sports with high intensity intermittent character (e.g., game sports like soccer, ice hockey, and handball) with a substantial anaerobic energy contribution. Also, the results might be of interest for endurance athletes competing in sports using a masstart that involves repetitive high intensity elements that are decisive for the race outcome (e.g., fast accelerations during the start, sprint attacks, and finish spurt).

AUTHOR CONTRIBUTIONS

Conception and design of the experiments: TS, Performance of the experiments: TS, and GB. Data analysis: TS, and GB. Preparation of the manuscript: TS, and GB. Both authors read and approved the final manuscript.

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Eleven-Week Preparation Involving Polarized Intensity Distribution Is Not Superior to Pyramidal Distribution in National Elite Rowers

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Polarized (POL) training intensity distribution (TID) emphasizes high-volume low-intensity exercise in zone (Z)1 (<first lactate threshold) with a greater proportion of high-intensity Z3 (>second lactate threshold) compared to Z2 (between first and second lactate threshold). In highly trained rowers there is a lack of prospective controlled evidence whether POL is superior to pyramidal (PYR; i.e., greater volume in Z1 vs. Z2 vs. Z3) TID. The aim of the study was to compare the effect of POL vs. PYR TID in rowers during an 11-wk preparation period. Fourteen national elite male rowers participated (age: 20 ± 2 years, maximal oxygen uptake ($\dot{V}O_{2max}$): 66 ± 5 mL/min/kg). The sample was split into PYR and POL by varying the percentage spent in Z2 and Z3 while Z1 was clamped to ~93% and matched for total and rowing volume. Actual TIDs were based on time within heart rate zones (Z1 and Z2) and duration of Z3-intervals. The main outcome variables were average power in 2,000 m ergometer-test ($P_{2,000\,m}$), power associated with 4 mmol/L [blood lactate] ($P_{4[BLa]}$), and $\dot{V}O_{2max}$. To quantify the level of polarization, we calculated a Polarization-Index as log (%Z1 × %Z3 / %Z2). PYR and POL did not significantly differ regarding rowing or total volume, but POL had a higher percentage of Z3 intensities (6 ± 3 vs. 2 ± 1%; $p < 0.005$) while Z2 was lower (1 ± 1 vs. 3 ± 2%; $p < 0.05$) and Z1 was similar (94 ± 3 vs. 93 ± 2%, $p = 0.37$). Consequently, Polarization-Index was significantly higher in POL (3.0 ± 0.7 vs. 1.9 ± 0.4 a.u.; $p < 0.01$). $P_{2,000\,m}$ did not significantly change with PYR (1.5 ± 1.7%, $p = 0.06$) nor POL (1.5 ± 2.6%, $p = 0.26$). $\dot{V}O_{2max}$ did not change (1.7 ± 5.6%, $p = 0.52$ or 0.6 ± 2.6, $p = 0.67$) and a small increase in $P_{4[BLa]}$ was observed in PYR only (1.9 ± 4.8%, $p = 0.37$ or −0.5 ± 4.1%, $p = 0.77$). Changes from pre to post were not significantly different between groups in any performance measure. POL did not prove to be superior to PYR, possibly due to the high and very similar percentage of Z1 in this study.

Keywords: rowing, training intensity distribution, elite athletes, interval training, high intensity, high volume, training zones

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INTRODUCTION

Olympic rowers aim to cover the distance of 2,000 m faster than their opponents, with world best times varying from 5:18 to 7:08 min. For this purpose, rowers generate an average power of ∼590 W (Voliantis and Secher, 2009) and exhibit an outstanding maximal oxygen uptake ($\dot{V}O_{2max}$; Secher, 1993; Ingham et al., 2002) with extreme acidosis and metabolic stress (Nielsen, 1999).

To prepare for this kind of physical exertion and performance, elite rowers perform most of their training time with high-volume and (relatively) low-intensity exercise (Nybo et al., 2014), often referred to as "basic endurance training," which is quite demanding in rowing as indicated by an oxygen uptake exceeding 3.5 L/min (Secher, 1993) and forces >500 N per stroke (Roth et al., 1993). The high metabolic and muscular demands limit high-volume low-intensity rowing sessions to 90–100 min to avoid impaired stroke technique. With increasing boat velocity the energy expenditure increases 2.2- to 2.4-fold (Secher, 1993) ultimately forcing the athlete to row as efficiently as possible during each session. In addition to the rowing sessions, most rowers implement 2–3 strength-training sessions per week into their training schedules, thereby increasing the exhaustive character of a rower's preparation for competition.

Over the last three decades the total training volume in elite rowing elevated by 66%, augmenting to ∼23 h/wk in Norwegian rowers during the 90's (Fiskerstrand and Seiler, 2004) and is estimated to peak at ∼29 h/wk nowadays (Nielsen, 2009/2017). Based on temporal limits and high workload of today's elite rowers we may assume that total training volume is near its functional maximum. As the medal winners' 2,000 m boat speed still increases by ∼0.12% per year (Kleshnev and Nolte, 2011), optimization of training schedules, especially by altering the intensity distribution (TID) might be a worthwhile resource to enhance performance.

Within the literature a three-zone intensity model is applied to quantify the TID. The model is based on the following physiological benchmarks: Zone 1 (Z1) is defined as low-intensity exercise with low levels of blood lactate below first lactate or ventilatory threshold. Zone 2 (Z2) refers to elevated and accumulated blood lactate concentration also called "lactate threshold training" identified as an intensity between the first and second lactate or ventilatory threshold. Finally, Zone 3 (Z3) refers to high-intensity exercise above the second lactate or ventilatory threshold (Kindermann et al., 1979; Seiler and Kjerland, 2006). Common additional parameters to demarcate the three intensity zones are based on blood lactate levels [BLa] of <2 mmol/L (Z1), 2–4 mmol/L (Z2), and >4 mmol/L (Z3) as well as certain percentages of maximal heart rate or maximal oxygen uptake. Noteworthy, national sport governing bodies and rowing federations often apply five-zone models to differentiate training intensities more detailed (Seiler, 2010).

So far, few studies have described the TID in rowing, especially on an elite level. In 1998 Steinacker et al. reported German, Danish, Dutch, and Norwegian elite rowers spending 90–96% of their total training volume in Z1 but it remains uncertain to the reader how the remaining percentage was exactly split into Z2 and Z3 (Steinacker et al., 1998). Single case studies reported a TID of 85% in Z1 (Nybo et al., 2014) in an elite lightweight rower from Denmark and ∼81% in Z1 in a double Olympic champion from Norway (Seiler and Tønnessen, 2009), with both reports not specifying the percentages spent in Z2 and Z3. Most analyses so far report a pyramidal TID, i.e., decreasing amount of training spent in Z1, Z2 and Z3. German junior rowers e.g., exhibited a TID of ∼95-3-2 (i.e., percentage in Z1, Z2, Z3) during the last 9 weeks before the first competition (Guellich et al., 2009) and nine successful Olympic rowers from New Zealand featured a TID of 77-17-6 (Plews et al., 2014). A successful French rower employed a TID of 45% Z1 and 55% Z2 (Lacour et al., 2009), notably a TID emphasizing "threshold" intensity. Only one investigation so far reported a polarized (POL) TID of 93-2-5 in a Belgian elite sculler (Bourgois et al., 2013). POL is characterized by a relatively high amount of volume performed in Z1 and Z3, with less volume in Z2. Taking into account that rowing is a high-intensity sport and being aware of several reports from other endurance disciplines like e.g. running, cycling or cross-country skiing (Stöggl and Sperlich, 2015), the long-term stimulus of POL may improve endurance performance with potentially less autonomic and hormonal stress and boredom, which is supported by experiments in club rowers who especially emphasized Z3-training (Driller et al., 2009; Ní Chéilleachair et al., 2016).

Several observational studies of national or world-class athletes from various sport disciplines like running (Billat et al., 2001) or cross-country skiing (Seiler and Kjerland, 2006; Sandbakk et al., 2011; Tønnessen et al., 2014) successfully applied a POL TID. Only one controlled study in 18 club rowers following a 28-day detraining period reported a similar increase of ergometer performance with POL (72-0-28) compared to a control group exaggerating low-intensity rowing (98-2-0; Ingham et al., 2008).

Integrating the findings of rowing studies as well as findings from other endurance sports (Neal et al., 2013; Stöggl and Sperlich, 2014) strong evidence exists that POL may be applied in high performance rowing, but this notion is drawn on two serious limitations: Firstly, performance benefits of POL have been concluded based on retrospective observations, but prospective randomized-controlled data on sub-elite or elite level rowers do not exist. Secondly, POL has been compared to static TIDs which do not change over weeks or months. From a methodological point of view, experiments involving static TIDs are convenient for scientists to compare differences between groups, but a static TID does not mirror real-training scenarios in high performance sports, in which TIDs are shaped "dynamically" with increasing percentages of Z2 and Z3 before competitions. Notably, this is recommended by the current scientific literature (Bangsbo et al., 2010; Tønnessen et al., 2014).

Altogether, numerous successful TIDs exist in rowing (i.e., POL and PYR), data from various disciplines and rowing are conflicting, and no prospective randomized-controlled investigation exists comparing POL to a dynamic TID in elite rowers. Therefore, we aimed to compare 11 weeks of a competition-preparation period involving POL to a dynamic PYR distribution in national elite rowers.

MATERIALS AND METHODS

Design

The present prospective study was conducted during the final 11 weeks of the preparation period, i.e., calendar week 3–14. Immediately after the study, the national qualification regatta to apply for the national team was scheduled. Fourteen national elite rowers participated in the study. Twelve (86%) rowed for Germany on international regattas in 2016, three rowers were lightweights. **Table 1** summarizes the rowers' anthropometric data. All rowers provided written informed consent to participate. The experimental protocol was approved by the ethical review board of the University of Ulm.

The rowers trained in two different training facilities (A;B) within Germany. Athletes could not be randomly assigned to PYR or POL, because several rowers trained in crew boats. Moreover, it was not possible to separate existing training squads for organizational reasons. To overcome this limitation, we allocated two groups in each of the two facilities to either PYR or POL. In each facility, one training group followed the traditional rowing schedule emphasizing high-volume low-intensity exercise and a pyramidal TID (PYR). The other group targeted a polarized TID model (POL). In facility A, one athlete of each group was excluded from the study due to illness or injury not related to the intervention. The 11-wk duration included pre- and post-test procedures to evaluate the changes in rowing performance and physiological variables.

Training Intervention

Training Intensity Zones

A three-zone training model was applied to quantify TID (Foster et al., 2001; Seiler and Kjerland, 2006; Seiler, 2010). The following three intensity zones were established based on a 5 × 4-min ergometer step test as described in detail below (Section Power Output at 2 and 4 mmol/L Blood Lactate): Z1 was defined as the intensity between 65% of maximal heart rate and the first lactate threshold or lactate-equivalent as described by Kindermann et al. (1979). Z2 was defined as the intensity between first lactate threshold and the second or individual lactate threshold as described by Dickhuth et al. (1991). Z3 was defined as an intensity above the second lactate threshold.

All intensities were related to the corresponding heart rates (HR) during the ergometer step test to allow for objective entries into the mandatory online training diary of the German Rowing Federation. The diary included information about the training mode, duration, distance, and intensity as well as information on days off and illness or injury. Entries of Z1 and Z2 sessions were based on time spent in corresponding HR-zones. HR was measured by the athletes' own HR-monitors and/or with the smartphone based rowing in Motion–App (In Motion Software & Sports Technology, Hanau, Germany) that was connected to a chest belt with Bluetooth data transmission (H7, Polar Electro, Oy, Finland). To avoid underestimation of Z3 sessions due to the delayed HR-response at high intensities, Z3 sessions were not documented by time in corresponding HR-zone, but by the total duration of the performed Z3-interval, as long as the maximal HR of the interval reached the individually defined Z3 HR-zone. Otherwise the interval was rated as Z2.

The diary logs were checked by the coaches and crosschecked by the research team for plausibility. After completion of the study, all data were exported (.csv files) and subsequently analyzed using the Python data analysis toolkit "pandas" (version 0.18.0, PyData Development Team) and the Scientific Computing Library "Scipy" (version 0.17.0, SciPy developers).

Notably, a basic framework of adequate training intensities was provided by rowing stroke frequency and pace prescribed by the coaches, which is a common practice in rowing (Plews et al., 2014).

TABLE 1 | Participants' anthropometric characteristics.

Variable	PYR	POL	p	d_{Cohen}
Standing height (cm)	193 ± 2	185 ± 7	0.029	−1.55
Body mass (kg)	93 ± 3	85 ± 11	0.138	−0.99
Age (years)	19 ± 1	21 ± 2	0.062	0.26
$\dot{V}O_{2max}$ (mL/min/kg)	64 ± 3	68 ± 7	0.171	0.74

PYR (n = 7), pyramidal training intensity distribution; POL (n = 7), polarized training intensity distribution; $\dot{V}O_{2max}$, maximal oxygen uptake.

Training Modes

Training differentiated four modes, namely (i) *Rowing*: involving boat and ergometer rowing, (ii) *Endurance*: other endurance training like running, cycling, swimming, etc., (iii) *Strength*: resistance training, machine-based or weight lifting, and (iv) *Other*: stretching, stability training, etc.

Training Intensity Distribution

The overall training of both groups included all four training modes (*Rowing, Endurance, Strength*, and *Other*). Based on the coaches' experience with their athletes, both groups targeted 16–18 h total training volume per week and ∼120 km of rowing per week. The general training schedule provided 2–3 sessions of strength training and 6–8 rowing sessions per week. The primary distinction between the two groups was the prescribed intensity distribution, with PYR including two to three Z2-sessions (e.g. 1 × 4 or 2 × 3 or 3 × 2 km) with not more than one session in Z3. In contrast, POL included 2-3 sessions of Z3 training (e.g. 2 × 2 km, 10 × 250 m; 6 × 1 km) while avoiding Z2 as much as possible.

To ensure high compliance, the general training prescription was discussed with the coaches of both groups before initiating the study. However, since preparation period is fundamental for competition success, the coaches were permitted to adapt the schedule depending on the athletes' particular needs, health status and environmental conditions.

Pre- and Post-measurements

During the first visit all rowers were medically examined by a licensed sports physician. The medical examination also included an electrocardiography at rest (CardioPart 12 Blue, Amedtec, Aue, Germany), an echocardiogram (Philips CX50, Phillips Medical Systems, Andover, MA, USA), and blood analysis to exclude iron deficiency and anemia. All rowers were declared free from cardiovascular disease and eligible to perform the exercise protocol and the study.

Afterwards, a series of rowing ergometer tests was conducted on two days (**Figure 1**) employing a Concept 2 Type D ergometer (Concept 2, Morrisville, USA) for all tests. The ergometer was modified with a load cell for force measurement and a rotary transducer to calculate the power output [Institut für Forschung und Entwicklung von Sportgeräten (FES), Berlin, Germany].

Power Output at 2 and 4 mmol/L Blood Lactate

After the physical examination, all rowers performed a 5 × 4-min incremental step test with 50 W increments per stage. The workloads ranged from 150 to 350 W in the lightweight and from 200 to 400 W in the open weight class rowers. During a 30-s break between each stage, 20 μL of capillary blood were sampled from the hyperemic earlobe and the level of blood lactate was immediately analyzed amperometric-enzymatically (C-Line, EKF, Barleben, Germany). A specialized software calculated power output at 2 and 4 mmol/L [blood lactate] ($P_{2[BLa]}$ and $P_{4[BLa]}$) using a polynomic fitting of the power and lactate data (Winlactat, Mesics, Münster, Germany). $P_{4[BLa]}$ is an accepted measure of rowing performance with standard errors of the estimate of 2,000 m ergometer performance amounting to 1.4–3.3% (Smith and Hopkins, 2012). We used 3.3% as the lower limit to identify worthwhile changes, since the performance level of our rowers was similar to those of previous reports (Nevill et al., 2011).

Two Thousand Meters Ergometer Test

All rowers performed an all-out 2,000 m ergometer test to evaluate maximal rowing ergometer performance, by covering the virtual distance of 2,000 m as fast as possible. The average power ($P_{2,000\,m}$) was recorded from the Concept 2 monitor afterwards. This test is employed worldwide in elite rowing to determine changes of maximal performance (Hahn et al., 2000; Mäestu et al., 2005; Smith and Hopkins, 2012). The standard error of the estimate of 2,000 m single-scull performance has been calculated to be 2.6% (Jürimäe et al., 2000). The error of measurement on Concept 2 rowing ergometers for $P_{2,000\,m}$ amounts to 1.3% (95%CI 0.9-2-9; Soper and Hume, 2004). We used this value to estimate the smallest worthwhile change in $P_{2,000\,m}$ (Smith and Hopkins, 2011).

Measurements of Maximal Oxygen Uptake

$\dot{V}O_{2max}$ was measured with a ramp test protocol that enables a linear increase in power and objective test termination (Winkert et al., 2016). Briefly, target power of the rowing ergometer was initially set to 160 W and increased 30 W/min (lightweight rowers) or 35 W/min (open weight class). The test automatically terminated in case the rowers failed to increase power within a 7-W range of five strokes. Gas exchange and ventilation were measured using a metabolic analyzer with a dynamic mixing chamber (Metamax 3x, Cortex Biophysics, Leipzig, Germany). The technical error of measurement of this device amounts to 0.03–0.21 L/min (95% confidence interval; Larsson et al., 2004). The system was calibrated prior to each test using ambient air and the manufacturers' calibration gas (16% O_2, 5% CO_2). A precision 3-L syringe (Hans Rudolph, Shawnee, USA) was employed to calibrate the flow sensor.

$\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ with increasing workload and averaged over a 30-s interval. $\dot{V}O_{2max}$ was considered when $\dot{V}O_2$ failed to increase with progressive work rate (leveling off) or at least a plateau of $\dot{V}O_2$ was present. A plateau was defined as an increase in $\dot{V}O_2 < 150$ mL/min, which is the most frequent definition in literature (Midgley et al., 2007). A leveling-off or plateau $\dot{V}O_2$ was found in all cases. In addition, respiratory exchange ratio at exertion was always >1.1 with [BLa] ≥ 8 mmol/L.

Polarization-Index

To quantify the individual level of periodization, we calculated a Polarization-Index based on the percentage, time, or distance trained in each intensity zone. The Polarization-Index was calculated as follows:

$$\text{Polarization} - \text{Index (a.u.)} = \log\left(Z1/Z2 \times Z3\right) \quad (1)$$

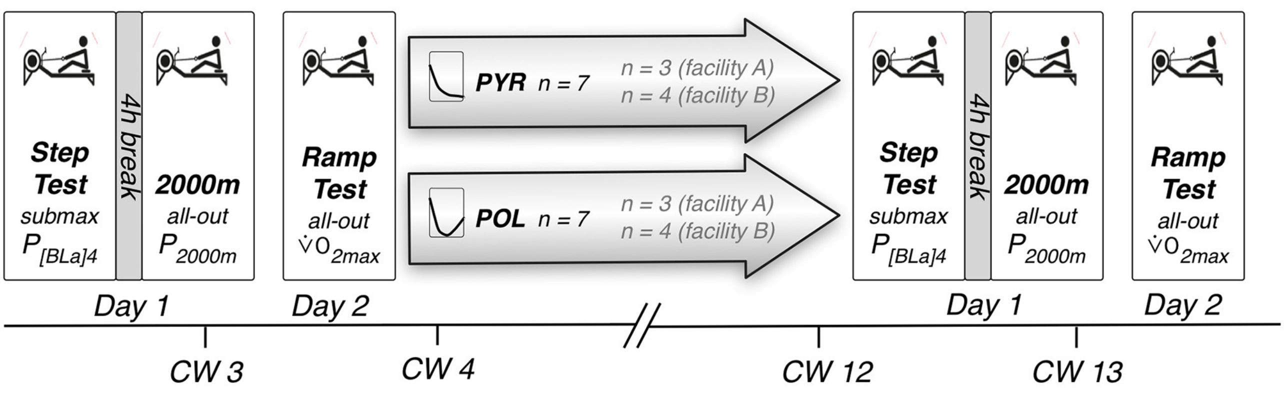

FIGURE 1 | Study and test design. $P_{[BLa]4}$, Power at blood lactate concentration of 4 mmol/L; $P_{2,000\,m}$, Average power in 2,000 m rowing ergometer test; $\dot{V}O_{2max}$, Maximal oxygen uptake; PYR, Pyramidal training intensity distribution; POL, Polarized training intensity distribution; CW, Calendar week.

If Zone 2 = 0, following formula avoided zero in the denominator:

$$\text{Polarization}-\text{Index (a.u.)} = \log\left(Z1/0.1 \times (Z3 - 0.1)\right) \quad (2)$$

If Z3 = 0, Polarization-Index was defined as zero.

In case of a Polarization-Index > 2.0 a.u., the TID was defined to be polarized, indicating an increasing level of polarization with higher values. If Polarization-Index was ≤2 a.u. the TID was defined as being not polarized.

In the context of this study, all TIDs with a Polarization-Index ≤ 2.0 a.u. were pyramidal or indifferent, but from a theoretical perspective, a Polarization-Index ≤ 2.0 can indicate at least five different TIDs, namely (i) a pyramidal TID (80-15-5; Polarization-Index = 1.4 a.u.), (ii) an inverse pyramidal TID (20-30-50; Polarization-Index = 1.5 a.u.), (iii) a *Lactate Threshold TID* (60-38-2; Polarization-Index = 0.5 a.u.), an indifferent TID (90-5-5; Polarization-Index = 2.0 a.u.), or a Long-Slow-Distance TID (100-0-0; Polarization-Index = 0.0 a.u.).

A Polarization-Index > 2.0 a.u. does not indicate a polarized distribution, if Z1 is smaller than Z3 (e.g., 40-0-60; PI = 4.4 a.u.). This kind of TID would probably be classified as *High Intensity Training* or *HIT*, since polarized distributions necessitate Z1 volume to be highest.

Even if we assume that a given Polarization-Index reflects the same degree of polarization, we cannot expect the same physiological response from different TIDs emerging in the same Polarization-Index. For example, a Polarization-Index of 2.3 a.u. can result out of 90-3-7 and 50-10-40. Nevertheless, the Polarization-Index seems useful to quantify the level of polarization of TIDs with Z1-percentages between 75 and 95%, which are frequently used in high performance sports (Seiler, 2010).

Statistical Analysis

All statistical procedures were calculated using the statistical package SPSS 21. Average data are expressed as arithmetic mean ± standard deviation, unless otherwise stated. To calculate differences between groups, a *t*-test was employed after testing for normal distribution using a Shapiro–Wilkinson-Test. A paired *t*-test was applied to calculate differences between pre and post-test. An unpaired *t*-test analyzed significant differences between training groups. Cohens d (d_{Cohen}) was calculated to estimate effect sizes (Cohen, 1988), defined as follows: trivial: 0–|0.2|, small: |0.2|–|0.6|, moderate |0.6|–|1.2|, large: |1.2|–|2.0|, very large: |2.0|–|4.0|, and infinite: > |4.0| (Hopkins, 2003).

A correlation analysis using Pearson's coefficient identified possible effects of volume spent in the specific training modes, number of days without training, training volume in Z1-Z3, Polarization-Index and changes in endurance variables (i.e., $P_{2,000\,m}$, $P_{2[BLa]}$, $P_{4[BLa]}$, $\dot{V}O_{2max}$). Effect sizes of correlation were defined as follows: trivial: 0.0, small: 0.1–0.3, moderate: 0.3–0.5, high: 0.5–0.7, very high: 0.7–0.9, nearly perfect: 0.9, and perfect 1.0 (Hopkins, 2003).

We dichotomized the outcome of the main variable $P_{2,000\,m}$ into $\Delta P_{2,000\,m}$ (≤1.3%; >1.3%) to distinguish between changes smaller or higher than the smallest worthwhile change and applied a Fishers' exact test to calculate if distributions between $\Delta P_{2,000\,m}$ and Group (PYR; POL), or Polarization-Index (≤2; >2) were different.

RESULTS

Training

Specific Training (Boat & Rowing Ergometer)

The rowing volume and sum of rowing sessions are summarized in **Table 2**. Rowing training was not significantly different between groups regarding absolute volume, duration or frequency. Small effect sizes indicated a slightly higher distance covered by PYR, while the number of training sessions was slightly higher in POL (**Table 2**).

Training Mode

The distribution of rowing (boat and ergometer) and strength training were not significantly different between groups, but there was a tendency for higher volume of *Endurance* and *Other* training in POL with moderate to large effects. Notably, the number of *Endurance* and *Other* sessions were significantly higher in POL compared to PYR, underlined by large effect sizes (**Table 3**).

Both groups did not differ regarding the days of illness ($p = 0.81$) amounting to a median of 3 days (min-max: 1–7) in PYR and 4 days (1-11) in POL.

Intensity Distribution

Figure 2 shows that percentage of training in Z1 was similar between PYR and POL (94 ± 3% and 93 ± 2%; $p = 0.37$, $d_{Cohen} = -0.33$), but Z2 was significantly higher in PYR (3 ± 2% and 1 ± 1%; $p < 0.01$; $d_{Cohen} = -1.27$) and Z3 was significantly higher in POL (2 ± 1% and 6 ± 3%; $p < 01$; $d_{Cohen} = 1.79$). This emerged into a significantly higher Polarization-Index in POL (1.9 ± 0.4 and 3.0 ± 0.7; $p < 0.01$; $d_{Cohen} = 1.93$).

The longitudinal differences in TID of both groups during the 11-wk intervention expressed by means of the Polarization-Index are displayed in **Figure 3**. The Polarization-Index was significantly higher in POL in calendar week 4, 5, 6, 7, 8, and 10 ($p = 0.00$ to 0.02). No significant differences in the Polarization-Index were found in the other weeks, although with a tendency to be greater in POL ($p = 0.19$ to 0.36) except of weeks 11 and 12. To note, the Polarization-Index clearly increased in PYR toward the end of the study period, starting in calendar week 11 (3.0 a.u.), thereby indicating a considerable increase of Z3-intensities.

TABLE 2 | Mean characteristics of the total rowing volume and sum of rowing sessions.

Variable	PYR	POL	*p*	d_{Cohen}
Rowing distance (km)	1334 ± 67	1255 ± 264	0.466	−0.41
Rowing duration (min)	5953 ± 315	5919 ± 1216	0.945	−0.04
Sessions (n)	80 ± 4	84 ± 13	0.414	0.42

PYR, pyramidal training intensity distribution; POL, polarized training intensity distribution.

TABLE 3 | Distribution of training modes during observation period.

Training mode	Duration (min/wk)				Percent (%/wk)				Sessions (1/wk)			
	PYR	POL	*p*	d_{Cohen}	PYR	POL	*p*	d_{Cohen}	PYR	POL	*p*	d_{Cohen}
Rowing	541 ± 28	537 ± 110	0.93	−0.05	58 ± 5	54 ± 9	0.35	−0.55	7.2 ± 0.3	7.7 ± 1.2	0.41	0.57
Strength	178 ± 32	149 ± 72	0.36	−0.52	19 ± 3	15 ± 7	0.18	−0.74	1.6 ± 0.4	1.3 ± 0.7	0.39	−0.53
Endurance	144 ± 30	202 ± 68	0.07	1.10	15 ± 3	21 ± 6	0.08	1.27	1.7 ± 0.4	3.0 ± 0.8	0.00	1.37
Other	68 ± 28	100 ± 29	0.06	1.12	7 ± 3	10 ± 3	0.07	1.00	2.2 ± 0.6	3.5 ± 1.2	0.03	1.37
Total	931 ± 50	990 ± 100	0.19	0.75					12.7 ± 0.8	15.5 ± 2.3	0.002	1.63

PYR, pyramidal training intensity distribution; POL, polarized training intensity distribution; Rowing, boat & rowing ergometer; Strength, resistance training; Endurance, other modes of endurance training than rowing (e.g., spinning, cycling, running); Other, all other kinds of training not mentioned before (e.g., stretching, stabilization training, Yoga).

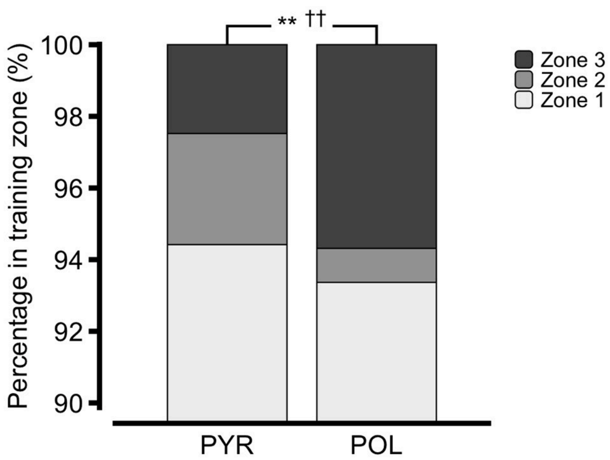

FIGURE 2 | Intensity distribution in boat & ergometer rowing. ** and ††: Percentage rowed in Z2 and Z3 differed between pyramidal (PYR) and polarized training intensity distribution (POL) (*p* < 0.01).

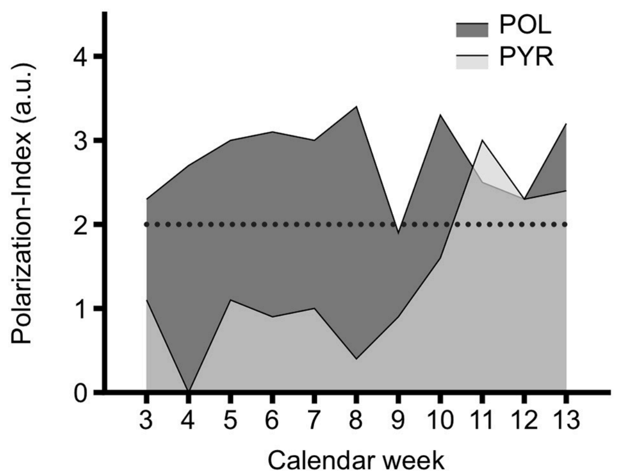

FIGURE 3 | Polarization-Index of a pyramidal (PYR) and a polarized rowing training group (POL) during 11 weeks of intervention and pre-/post-testing. Polarization-Index = log (%Zone 1 × %Zone 3 / %Zone 2). See text for details. Broken line indicates Polarization-Index of 2 a.u., which is defined being the cut off between polarized (> 2) and not polarized (≤2 a.u.) training intensity distribution. The high percentage of Zone 3 in calendar weeks 3 and 13 was due to the pre-/post-testing.

Performance

In the complete sample, $P_{2,000\,m}$ increased significantly ($p = 0.03$) from 443 ± 30 W to 449 ± 26 W, corresponding to an improvement in 2,000 m time of ~2 s (pre: 370.1 ± 8.7 s to post: 368.2 ± 7.2 s, representing a small effect ($d_{Cohen} = -0.24$). Average changes between PYR and POL or within PYR and POL from pre to post-test were trivial or small and not significant (**Table 4**).

$\dot{V}O_{2max}$, $P_{2[BLa]}$, $P_{4[BLa]}$ did not significantly change from pre to post or between groups. A small increase of average $P_{2[BLa]}$ and $P_{4[BLa]}$ was detected in PYR only, where three rowers (43%) improved $P_{4[BLa]}$ by more than 3.3% in contrast to POL with only one rower (14%) who improved above this threshold. The unbalanced improvement in $P_{2[BLa]}$ and $P_{4[BLa]}$ between groups is also reflected by small effect sizes in PYR and trivial effect sizes in POL (**Table 4**).

On an individual level five out of six (83%) rowers with POL improved $P_{2,000\,m}$ above the estimated error of measurement of 1.3% (95%CI 0.9-2-9; Soper and Hume, 2004). In PYR, four out of seven (57%) rowers improved $P_{2,000\,m}$ above 1.3% (**Figure 4**).

Training and Performance: Correlation Analysis

Correlation analysis indicated, that changes in $P_{2,000\,m}$ became smaller with greater volume of *Other* training like e.g., stretching ($r = -0.61$; $p = 0.03$).

Changes in performance variables ($P_{2[BLa]}$, $P_{4[BLa]}$, $P_{2,000\,m}$, $\dot{V}O_{2max}$, and duration in 2,000 m ergometer test) were not significantly correlated to total days without training (highest absolute $r = 0.11$ with $p = 0.71$), neither health related (highest absolute $r = 0.42$; $p = 0.18$) nor related to scheduled days off (highest absolute $r = 0.26$; $p = 0.41$).

A high correlation was found between changes in $\dot{V}O_{2max}$ and absolute weekly volume ($r = 0.58$; $p = 0.05$) or percentage ($r = 0.59$; $p = 0.04$) spent in Z2. However, average changes in $\dot{V}O_{2max}$ were small, amounting to 0.1 L/min which is within the technical error of measurement of 0.03–0.21 L/min (95% confidence interval) for the device used in this study (Larsson et al., 2004).

TABLE 4 | Changes in performance after 11 weeks of training in national elite rowers.

Variable	PYR						POL						PYR vs. POL	
	Pre	Post	Δ%	*n*	*p*	d_{Cohen}	Pre	Post	Δ%	*n*	*p*	d_{Cohen}	*p*	d_{Cohen}
$\dot{V}O_{2max}$ (mL/min/kg)	64 ± 3	64 ± 2	1.7 ± 5.6	6	0.522	0.00	68 ± 7	68 ± 7	0.6 ± 2.8	6	0.686	0.00	0.712	0.22
Duration 2,000 m test (s)	368.8 ± 7.6	367.0 ± 6.4	−0.5 ± 0.6	7	0.060	−0.26	372.0 ± 10	369.8 ± 8.4	−0.5 ± 0.9	6	0.221	−0.24	0.962	0.03
$P_{2,000m}$ (W)	447 ± 27	454 ± 24	1.5 ± 1.7	7	0.057	0.27	438 ± 36	444 ± 30	1.5 ± 2.6	6	0.258	0.00	0.916	0.06
$P_{2[BLa]}$ (W)	291 ± 26	298 ± 19	3.0 ± 5.6	7	0.232	0.31	297 ± 16	297 ± 27	0.2 ± 5.9	7	0.897	0.00	0.441	0.42
$P_{4[BLa]}$ (W)	336 ± 25	341 ± 20	1.9 ± 4.8	7	0.369	0.22	337 ± 17	336 ± 24	−0.5 ± 4.1	7	0.770	−0.05	0.369	0.50

PYR, Pyramidal training intensity distribution; POL, polarized training intensity distribution; $\dot{V}O_{2max}$, maximal oxygen uptake; $P_{2,000m}$, average power in 2,000 m rowing ergometer test; $P_{2[BLa]}$ and $P_{4[BLa]}$, Power output with [blood lactate] 2 and 4 mmol/L. PYR vs. POL was calculated from the absolute difference between pre- and post-test of each group.

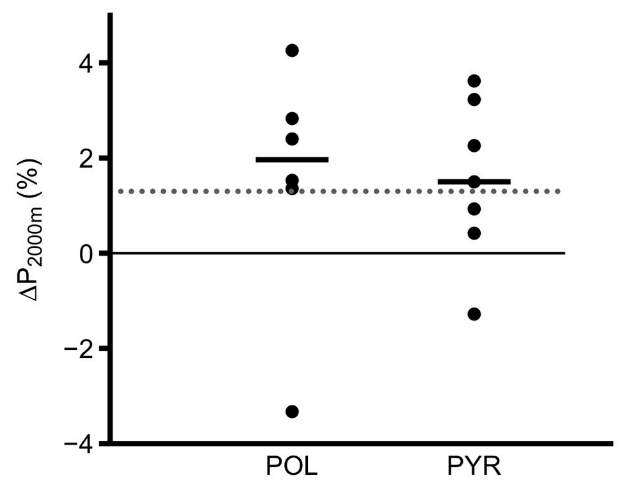

FIGURE 4 | Individual change of average power in 2,000 m rowing-ergometer test ($P_{2,000\,m}$) after 11-weeks between rowers following a polarized (POL) or pyramidal (PYR) training intensity distribution. The dashed line corresponds to estimated error of measurement for $P_{2,000\,m}$ on Concept 2 rowing ergometers of 1.3% according to Soper and Hume (2004). Short lines indicate median of each group.

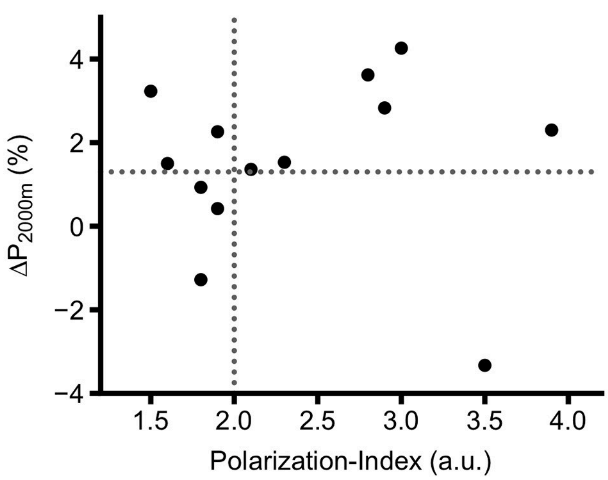

FIGURE 5 | Individual change (%) of average power in 2,000 m rowing ergometer test ($P_{2,000\,m}$) in 14 highly trained competitive U23 rowers. Horizontal dashed line indicates Polarization-Index of 2, which is defined being the cut off for polarized training intensity distribution (see text for details).Vertical dashed line indicates 1.3%, being the estimated error of measurement for $P_{2,000\,m}$ according to Soper and Hume (2004).

Negative correlation coefficients indicated, that the higher the absolute volume of Z3-training, the smaller the increase in $P_{2[BLa]}$ ($r = -0.56$; $p = 0.02$) and $P_{4[BLa]}$ ($r = -0.53$; $p = 0.05$). Similar results were obtained for percentage of Z3 and $P_{2[BLa]}$ ($r = 0.63$; $p = 0.02$) and $P_{4[BLa]}$ ($r = -0.59$; $p = 0.03$). In line with the previous result, smaller changes in $P_{2[BLa]}$ ($r = -0.58$; $p = 0.03$) and $P_{4[BLa]}$ ($r = -0.64$; $p = 0.01$) were correlated with higher Polarization-Index.

Distribution of Worthwhile Change in 2,000 m Ergometer Test, Group, and Polarization-Index

Even though more rowers in the POL-group increased $P_{2,000\,m}$ (**Figure 4**, **Table 4**) the distribution between groups regarding the dichotomized variable change ≥1.3% vs. change <1.3% was not different (Fisher's exact: $p = 0.56$), basically due to an outlier with $\Delta P_{2,000\,m}$ of −3.3% (**Figure 4**).

Figure 5 indicates that—irrespective of the group allocation—six out of seven (86%) rowers with a Polarization-Index >2 increased $P_{2,000\,m}$ more than 1.3%. In contrast, only three out of six rowers (50%) with a Polarization-Index ≤2 improved their $P_{2,000\,m}$ above the smallest worthwhile change. However, distribution between the dichotomized variable *Polarization-Index* (≤2.0; >2.0) vs. $\Delta P_{2,000\,m}$ (≤1.3%; >1.3%) was not significantly different (Fishers exact test: $p = 0.27$).

DISCUSSION

We compared two TIDs (POL vs. real-life PYR) in national elite rowers with increasing percentage of Z3-training during the last 3 weeks of a 11-wk training period. Notably, percentage of Z1 was clamped to ~93% in both groups. In summary, POL did not show to be significantly superior to PYR regarding any physiological determinant of rowing performance, but small effects indicated improved $P_{2[BLa]}$ and $P_{4[BLa]}$ in PYR only. However, irrespective of the groups, we observed a higher percentage of worthwhile improvements regarding $P_{2,000\,m}$, which is the key variable in rowing, when the Polarization-Index was ≥2.1 a.u.

On a group level both TID models allowed for improvements in $P_{2,000\,m}$, which is the most reliable and accepted surrogate measure of rowing performance (Hahn et al., 2000; Mäestu et al., 2005). Also Ingham et al. who compared POL to a low-intensity group, did not find POL to be superior in rowers, but in contrast to our results, the maximal oxygen uptake increased in both of their groups probably attributable to the much lower training status of those club rowers who were 13% slower in the 2000 m ergometer test compared to our athletes (Ingham et al., 2008). The athletes in our study were highly trained rowers including several medalists of Junior and U23 world championships, and it is well-known that significant and worthwhile improvements in maximal oxygen uptake are not easily achieved in this group of athletes.

Data from other endurance athletes (e.g., cyclists and runners) suggested, that POL might be superior regarding key endurance variables including $\dot{V}O_{2max}$, $P_{2[BLa]}$, $P_{4[BLa]}$, or time-trial performance (Neal et al., 2013; Stöggl and Sperlich, 2014) and confirmed by several uncontrolled training studies using observational data (Billat et al., 2001; Seiler and Kjerland, 2006; Sandbakk et al., 2011; Tønnessen et al., 2014) and also studies emphasizing high-intensity in rowers (Ní Chéilleachair et al., 2016).

We will therefore briefly discuss possible reasons why there were no clear differences in important physiological determinants between POL and PYR, including illness, training volume, mode, and TID.

Illness

Due to the typical rough weather conditions between January and March in central Europe, the pre-competition period of the rowers in our study was frequently disturbed by minor illnesses like colds and upper respiratory tract infections. Several athletes in our group experienced minor illnesses with the cancellations of single and multiple training sessions. However, based on the training diaries and our statistical analysis we did not detect any significant correlation between days of illness and performance outcome or any differences between groups. As the athletes may not have always reported re-scheduling of training due to minor illness (e.g., substituting cycle ergometer for rowing) it may be possible that mild infectious diseases have affected the outcome of the study. However, it is noteworthy that frequent re-scheduling is a real-life circumstance within the training process thereby constantly altering the prescribed TID.

Training Volume

Data concerning the precise training volumes of high performance rowers are scarce. The average weekly volumes of groups and single cases vary from 102 km/wk (Seiler and Tønnessen, 2009), 111.9 ± 43.7 km/wk (Tran et al., 2013), 119 km/wk (Lacour et al., 2009), 124 km/wk (Mikulic, 2011), 127 km/wk (Bourgois et al., 2013) to 135 km/wk (Nybo et al., 2014). Based on the aforementioned reports, the average training volume of elite rowers amounts to ∼120 km/week. In our study rowing training averaged 114 km/wk (POL) to 121 km/wk (PYR) which appears to be relatively high since most of our rowers were U23-rowers, who generally train less then world-class rowers of higher age, but reasonably more than juniors who row ∼97.1 ± 19.5 km/wk (Guellich et al., 2009). We therefore assume, that training volume in our study was *per-se* high enough to allow for changes in performance, independent of alterations in TID.

Volume of *Endurance* and *Other* training was moderately higher in POL. The number of the according sessions was significantly higher in POL with even large effect sizes (**Table 3**). While the high volume of non-specific endurance training was without negative effects, *Other* training (e.g., stretching) was obviously not effective above a certain threshold, as indicated by the negative correlation with $P_{2,000\,m}$.

Duration of the Intervention

The intervention period of 11 weeks is generally long enough to allow for physiological adaptations and is comparable to studies in elite (Stöggl and Sperlich, 2014) or sub-elite athletes (Neal et al., 2013).

Training Intensity Distribution

In our study the percentage of Z2 and Z3 was significantly different between PYR and POL with large effect sizes, indicating a relevant difference between groups in intensities near and above lactate threshold. However, the accumulated percentage of training in Z2 and Z3 did not exceed 7% in any group, which is very similar to classical rowing data (Steinacker et al., 1998; Guellich et al., 2009) but appears to be relatively low compared to the majority of current data in rowers varying between 7% (Bourgois et al., 2013), 15% (Nybo et al., 2014), 19% (Seiler and Tønnessen, 2009), and 23% (Plews et al., 2014), and as well as studies investigating POL involving other disciplines [20% (Neal et al., 2013) and 32% (Stöggl and Sperlich, 2014)]. Thus, we assume that the equally low percentage spent in Z2 and Z3 was not a sufficient stimulus to improve e.g., oxygen uptake, since high-intensity exercise is more effective in inducing central adaptations, as reported in highly trained cyclists (Laursen et al., 2002). In addition, our study clearly indicates that a polarized TID is not superior as such, but necessitates an optimal and probably higher sum of Z2 and Z3 intensities than realized by our POL-group. Obviously, POL requires an optimal and probably greater overall proportion of Z2- and Z3-intensitiy in contrast to the TID accomplished by our POL-group.

As recommend by the scientific literature (Bangsbo et al., 2010; Tønnessen et al., 2014) our study involved an increase in intensity over time especially in PYR to taper for the first national trials. Since especially PYR increased Z3 toward the end of the study, which is a real-training procedure, and since greater amounts of Z3 are reported to introduce rapid adaptions (Driller et al., 2009; Ní Chéilleachair et al., 2016), the great amount of Z3 in PYR during the last 2 weeks of the study period suggests, that pronounced and short periods of polarized training after several weeks of Z1 and Z2 training are a sufficient stimulus to improve performance. We assume, this effect of real-life TID very likely contributed to the lack of differences between POL and PYR.

Due to the aforementioned reasons including illness, fatigue or environmental conditions, some rowers in POL and PYR showed a greater "polarization" than others, as expressed by the Polarization-Index. Interestingly, we found more frequent improvements of $P_{2,000\,m}$ in those rowers who trained more polarized, irrespective of the group they were allocated to. Judging from the plot in **Figure 5**, we observed (with the exception of one outlier) that higher levels of polarization led to an increase of more than 1.3% (i.e., the estimated error of measurement) in $P_{2,000\,m}$, especially if Polarization-Index was >2.3 a.u. The notion, that variation including polarization needs to be consequently implemented to offer considerable advantages is plausible, because other studies reported increases of performance and/or $\dot{V}O_{2max}$ in rowers after high intensity-interventions between four (Driller et al., 2009) and eight weeks (Ní Chéilleachair et al., 2016). Since the average changes in $P_{2,000\,m}$ were not related to any physiological variable, other factors including efficiency and pacing may have accounted for the changes.

$P_{4[BLa]}$ is an established and valuable parameter to assess performance in rowing (Ingham et al., 2002; Smith and Hopkins, 2012) and a relevant fitness marker for many high performance coaches in rowing (Altenburg et al., 2012). Surprisingly, we did not find increases of $P_{2[BLa]}$ and $P_{4[BLa]}$ in POL, but small and more frequent improvements of $P_{4[BLa]}$ in PYR. This is in line with others, also reporting minor improvements in $P_{4[BLa]}$ with POL compared to a control group emphasizing low-intensity (Ingham et al., 2008).

According to our data, the higher percentage of Z3 (or the lower percentage of Z2) in POL contributes to the unaltered or even lowered $P4_{[BLa]}$ values in POL, as indicated by the high negative correlation between $P4_{[BLa]}$ and Polarization-Index or percentage of Z3. The notion, that Z2 training is essential for improvements in rowing performance is in line with other reports on successful elite rowers, whose training schedule always incorporated higher percentage of Z2-training, as indicated by data from New Zealand (Plews et al., 2014), Norway (Seiler and Tønnessen, 2009), and Denmark (Nybo et al., 2014). In addition, coaches of the POL-group reported (but did not quantify) that during the intervention period, the speed in Z1 was partially lower than before the study, to allow for recovery from fatigue inducing Z3 sessions. Since energy expenditure increases with boat speed by 2.2- to 2.4-fold power (Secher, 1993), we assume that the sessions at the lower end of the T1-range with low metabolic cost and muscular force were insufficient to further stimulate adaptions, thereby explaining the lack of improvement in POL. Differences of TID within Z1 are probably relevant to induce further adaptations, however, since we did not collect the necessary data, this notion warrants further investigation.

Limitations

Coaches and athletes volunteered to participate in the study and were fully informed about the two training regimes, but the scattering of the TIDs within the POL group indicates that some rowers did not entirely follow the training program in the same consequence. This limitation of our study was attributable to concerns by coaches and athletes to adopt a new TID with the possibility for non-functional overreaching. Further, minor illnesses and environmental factors caused elimination or altering of sessions with higher intensity, which might not have been reported in the diaries. In addition, the athletes in our study rowed in different boat types, ranging from single sculls to crew boats like four and quadruple sculls. Rowing in crew boats hinders the strict individual adherence to a prescribed TID, because the individual rower has to adapt to a given pace that emerges from the skills and physiological capacity of the crew, which also contributed to the scattering of individual TIDs and physiological changes, furthermore partly explaining the differences to studies in e.g., cyclists. Another limitation of our study is that the calculation of the TIDs is not based on HR-logfiles, but on the rowers' diary entries, based on their HR-measurements, time, and distance trained in each zone. The lack of HR-logfiles for direct analysis hindered us to distinguish between training intensities within a given intensity zone. Nevertheless, we cross-checked the entries with the coaches and associated rowers to overcome this limitation. An additional measurement after 8 weeks of the study would have theoretically allowed to quantify the impact of the high-intensity training in PYR during the last three weeks of the study (**Figure 3**). However, the interruption of the training process due to several days of obligatory tapering before the measurements and two additional days of testing would have been an unrealistic training scenario, thereby causing another limitation and moreover not acceptable by the coaches and athletes. Finally, athletes were inevitably aware of the group (POL or PYR) they were allocated to. We therefore cannot exclude expectancy effects.

CONCLUSION

We conclude that on a group level, POL is not superior to a dynamic, real-life PYR distribution when percentage of Z1 is clamped to ∼93%. However, it seems POL can have ergogenic effects, i.e., improved $P_{2,000\,m}$, if applied consistently and with a Polarization-Index ≥2.3 a.u. Taking previous data of elite non-rowing athletes into account, we assume that higher percentage of Z3 is necessary to achieve potential ergogenic superiority of POL compared to PYR.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of ethical review board of the University of Ulm with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by ethical review board of the University of Ulm.

AUTHOR CONTRIBUTIONS

GT: Planned and designed the study, conducted measurements, analyzed the data, prepared the manuscript. KW: Planned and designed the study, conducted measurements, analyzed the data, edited the manuscript. MS: Conducted measurements, edited the manuscript. JS: Designed the study, edited the manuscript. MB: Analyzed the data. BS: Designed the study, analyzed the data, edited the manuscript.

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The Mucosal Immune Function Is Not Compromised during a Period of High-Intensity Interval Training. Is It Time to Reconsider an Old Assumption?

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Purpose: The aim of the study was to evaluate the mucosal immune function and circadian variation of salivary cortisol, Immunoglobin-A (sIgA) secretion rate and mood during a period of high-intensity interval training (HIIT) compared to long-slow distance training (LSD).

Methods: Recreational male runners (n = 28) completed nine sessions of either HIIT or LSD within 3 weeks. The HIIT involved 4 × 4 min of running at 90–95% of maximum heart rate interspersed with 3 min of active recovery while the LSD comprised of continuous running at 70–75% of maximum heart rate for 60–80 min. The psycho-immunological stress-response was investigated with a full daily profile of salivary cortisol and immunoglobin-A (sIgA) secretion rate along with the mood state on a baseline day, the first and last day of training and at follow-up 4 days after the last day of training. Before and after the training period, each athlete's running performance and peak oxygen uptake ($\dot{V}O_{2peak}$) was determined with an incremental exercise test.

Results: The HIIT resulted in a longer time-to-exhaustion (P = 0.02) and increased $\dot{V}O_{2peak}$ compared to LSD (P = 0.01). The circadian variation of sIgA secretion rate showed highest values in the morning immediately after waking up followed by a decrease throughout the day in both groups ($P < 0.05$). With HIIT, the wake-up response of sIgA secretion rate was higher on the last day of training ($P < 0.01$) as well as the area under the curve (AUC_G) higher on the first and last day of training and follow-up compared to the LSD (P = 0.01). Also the AUC_G for the sIgA secretion rate correlated with the increase in $\dot{V}O_{2peak}$ and running performance. The AUC_G for cortisol remained unaffected on the first and last day of training but increased on the follow-up day with both, HIIT and LSD ($P < 0.01$).

Conclusion: The increased sIgA secretion rate with the HIIT indicates no compromised mucosal immune function compared to LSD and shows the functional adaptation of the mucosal immune system in response to the increased stress and training load of nine sessions of HIIT.

Keywords: circadian rhythm, cortisol, diurnal profile, endurance, high-volume training, immunoglobin-A, periodization

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INTRODUCTION

The exercise duration and intensity are key components to design training programs, stimulate adaptation and maximize performance of the modern day endurance athlete (Hydren and Cohen, 2015). Especially short intervals of 2–8 min at 90–95% of maximal heart rate (HR_{max}) interspersed with periods of incomplete recovery known as high-intensity interval training (HIIT) are applied to maximize central and peripheral adaptation (Buchheit and Laursen, 2013a,b; Ronnestad et al., 2014, 2016; Stoggl and Sperlich, 2014, 2015; Sylta et al., 2016). When performing three training sessions per week for 8 weeks the HIIT (e.g., 4 × 4 min) significantly increased the peak oxygen uptake ($\dot{V}O_{2peak}$) while no improvements occurred with the long-slow distance (LSD) running at 70% of HR_{max} for 45 min (Helgerud et al., 2007). The LSD sessions in the latter study however were fairly short while longer training sessions including low intensity have a small effect on $\dot{V}O_{2peak}$ (Stoggl and Sperlich, 2014).

Still the superior benefits of HIIT to improve $\dot{V}O_{2peak}$ have been shown multiple times in recreational and elite athletes among various endurance sports including running, cycling, rowing, and cross-country skiing (Helgerud et al., 2007; Ronnestad et al., 2014, 2016; Ni Cheilleachair et al., 2017). Despite the promising effects of HIIT however, the question arises among athletes, coaches and scientists whether the training load of several HIIT sessions within a short period of time might compromise the mucosal immune function. Especially the chronic exposure to high training loads has generally been assumed to increase the incidence of upper-respiratory tract infection (URTI; Trochimiak and Hubner-Wozniak, 2012).

A practical method to assess the stress-response from a psycho-immunological perspective during periods of intensified training is the combined assessment of the circadian variation of biomarkers in saliva and mood state (Papacosta et al., 2013; Born et al., 2016). While the concentrations of enzymes, hormones, and anti-bacterial compounds are far lower in saliva than in blood samples the relative changes in response to exercise are highly correlated to the blood serum (Cadore et al., 2008; VanBruggen et al., 2011; Tanner et al., 2014). The non-invasive collection of saliva allows a greater sampling rate and in an athletic population the entire circadian variation can be investigated with minimal interference in the daily training and recovery routines (Gatti and De Palo, 2011; Papacosta and Nassis, 2011).

Salivary immunoglobin-A (sIgA) and cortisol are biomarkers of particular interest when investigating the psycho-immunological stress-response during periods of intensified training. In ultra-marathon runners the extreme competition load acutely decreased the sIgA secretion rate and increased the levels of cortisol immediately after the exercise (Gill et al., 2014). Interestingly, low sIgA correlated with a high susceptibility of URTI and number of sick days during a period of polarized endurance training including both, continuous and interval training session (Ihalainen et al., 2016). Also an inverse correlation between levels of cortisol and sIgA secretion rate has been shown (Hucklebridge et al., 1998) and a potential decisive role of cortisol on the exercise-induced immune suppression during periods of intensified training discussed (Gleeson, 2007; He et al., 2010). Especially high-intensity exercise substantially increases the levels of cortisol (Allgrove et al., 2008). Therefore, the question arises whether the repeated exposure to HIIT over a prolonged period of time would compromise the mucosal immune function despite the tempting ergogenic effects including improved $\dot{V}O_{2peak}$.

Earlier studies however mostly investigated the mucosal immune function with single pre- and post-training saliva samples (He et al., 2010; Gill et al., 2014; Ihalainen et al., 2016). Due to the dramatic decrease of cortisol and sIgA from early morning throughout the day (Hucklebridge et al., 1998; Rohleder et al., 2007), a full daily profile is warranted to investigate the circadian variation of these biomarkers of interest. Therefore, the aim of the study was to evaluate the mucosal immune function and circadian variation of salivary cortisol, sIgA secretion rate and mood during a period of nine sessions of HIIT performed within 3 weeks compared to LSD. The hypothesis was that the HIIT would increase levels of salivary cortisol, reduce sIgA secretion rate and impair mood thereby showing a more pronounced psycho-immunological stress-response and compromised mucosal immune function compared to the LSD.

METHODS

Subject Characteristics

For the present investigation, 28 recreational endurance runners were assigned into two groups performing either HIIT (n = 16, age: 25 ± 4 years, body mass: 76 ± 5 kg, body height: 179 ± 6 cm) or LSD (n = 12, age: 25 ± 3 years, body mass: 77 ± 11 kg, body height: 182 ± 5 cm). After being informed about the potential risks and benefits of the study involved, all runners gave their written consent to participate. The study was approved by the Ethical Committee of the University of Wuppertal and performed in accordance with the Declaration of Helsinki.

Study Design

Each athlete completed nine sessions of either HIIT or LSD within a period of 3 weeks with at least 1 day between the sessions (Stoggl and Sperlich, 2014) in addition to their routine aerobic training (4.0 ± 2.0 vs. 3.8 ± 1.6 h/week with the HIIT and LSD group, respectively) as performed previously (Ronnestad et al., 2014; Faiss et al., 2015). Before (Pre-) and after (Post-) the training period all participants performed an incremental test to exhaustion for the determination of running performance, i.e., time-to-exhaustion (TTE), as well as variables related to the cardio-respiratory and metabolic capacity. For each individual Pre- and Post- was scheduled on the same time of the day and performed with the same pair of running shoes within the same ambient air condition (20 ± 1°C and 36 ± 4% relative humidity).

Each HIIT session was initiated with a 10-min warm-up of moderate intensity running at 70% of maximum heart rate (HR_{max}) including short bouts (30–45 s) with a higher running intensity to prepare the cardio-respiratory and metabolic system for the upcoming intervals. After the warm-up, the participants performed 4 × 4-min intervals with an exercise intensity corresponding to the individuals 90–95% of HR_{max} interspersed with 3 min of active recovery corresponding to 70% of HR_{max} (Helgerud et al., 2007). The HR data were recorded and each runner reached in at least 94% of all intervals (i.e., 34 of 36 possible intervals during the training period) the targeted exercise intensity of >90% of HR_{max} to be included in the statistical analysis. Due to the delayed HR response at the onset of exercise the athletes were instructed to reach the targeted HR zone (90–95% of HR_{max}) within the first 60–90 s of each interval as recommended previously (Helgerud et al., 2007). The LSD was performed continuously at 70–75% of HR_{max}. The duration for each LSD session was 60, 70, and 80 min for the first, second and third week of training, respectively.

In order to investigate the psycho-immunological stress-response to nine sessions of either HIIT or LSD, saliva samples along with questionnaires were taken on a baseline day before the start of the study, the first (T1) and last (T9) day of training. The follow-up measurement was performed on the day of the post-test 4 days after the last day of training (**Figure 1**).

Data Collection

Cardio-Respiratory and Metabolic Response

The incremental running test was performed on a treadmill (H/P Cosmos, Mercury, Nussdorf-Traunstein, Germany) and initiated with a running velocity of 2.4 m/s. Subsequently, the running velocity was increased by 0.4 m/s in 5-min intervals until voluntary exhaustion. The incremental test was performed at 1% inclination to simulate the missing air resistance and drag forces of outdoor running (Gore, 2000). Maximal effort was considered when the runners met three of the following four criteria: (1) $\dot{V}O_2$ showed a leveling-off defined as an increase of $\dot{V}O_2$ of <2.1 mL/kg/min (Taylor et al., 1955), (2) respiratory exchange ratio > 1.05, (3) HR ≥ 90% of the age-predicted HR, (4) ratings of perceived exertion ≥18 on Borg's 6–20 scale (Borg, 1970).

During the incremental running test, the participants were equipped with an open-circuit breath-by-breath gas analyzer (MetaMax3B_R2, Cortex Biophysik GmbH, Leipzig, Germany) breathing through a turbine flowmeter which was attached to a proper fitting face mask covering the mouth and nose (7,450 Series V2 TM Mask, Hans Rudolph Inc., Shawnee, USA). The HR was collected time aligned with the $\dot{V}O_2$ data using a chest belt (H7, Polar Electro Oy, Kempele, Finland). Before each test the oxygen (O_2) and carbon dioxide (CO_2) sensors of the gas analyzer were 2-point calibrated to ambient air (20.93% O_2 and 0.03% CO_2) and calibration gas containing 15% O_2 and 5% CO_2 (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany) to anticipate the expiratory gas compound. The turbine's flow volume was calibrated using a 3-L syringe (M9474-C, Medikro Oy, Kuopio, Finland). The levels of blood lactate concentration were determined in the capillary blood sampled from the left ear lobe (LactatePro2, LT-1730, Arkray, Kyoto, Japan) and used for the subsequent linear extrapolation of the running velocities at 2 and 4 mmol/L blood lactate concentration.

Psycho-Immunological Stress-Response

In order to assess the acute exercise induced stress-response as well as the circadian variation of the markers of interest, on each day of measurement (baseline, T1, T9, and follow-up) five saliva samples were taken: (1) immediately after waking up, (2) 30 min after waking up, (3) immediately before training, (4) immediately after training, and (5) before going to bed as described previously (Rohleder et al., 2007; Born et al., 2016).

To collect the saliva samples all athletes received the following instructions: (1) not to eat and drink (other than plain water) or brushing teeth for 30 min beforehand to avoid blood contamination of the saliva sample, (2) rinse the mouth with water and swallow any remaining fluid, (3) start a stopwatch and passively collect saliva in the mouth while resting in a seated position with the head tilted slightly forward for exactly 2 min, (4) spit the accumulated saliva through a sterile polypropylene straw into a polypropylene tube (Sali-Cap Tubes, IBL International, Hamburg, Germany), (5) store the saliva tube in the freezer at −18°C and bring the sample to the lab the next morning for the analysis of cortisol and sIgA, as recommended previously (Granger et al., 2007). For the first sample of the day, the participants were instructed to collect the saliva immediately after waking up when the alarm went off while sitting at the edge of the bed. For the next 30 min the participants were allowed to walk around, take a shower and prepare the breakfast. They however were not allowed to eat, drink or continue sleeping. The exact time of the day for each saliva sample was reported in a specific protocol.

A scaling on the transparent polypropylene tube showed the volume of saliva collected. In case the collected saliva was <1 mL within the first 2 min the athletes continued collecting saliva for another 2 min. The additional collection time was reported in the protocol for the subsequent determination of saliva flow rate. Especially high-intensity exercise reduces the flow rate of saliva by enhancing sympathetic and/or attenuating the parasympathetic activation (Papacosta and Nassis, 2011). Therefore, the saliva flow rate was employed to calculate the secretion rate of sIgA from the absolute concentrations for any further statistical analysis (Allgrove et al., 2008; Papacosta and Nassis, 2011).

Along with the saliva sample, the athletes rated their current mood on a questionnaire adapted by Wilhelm and Schoebi (2007). The items included levels of stress, anxiety, annoyance, happiness, exhaustion, and energy ranked on a Likert scale from (1) not at all to (5) very much. After decoding, the mood was assessed by the sum of all items while a high score indicated vitality and well-being and a low score a suppressed mood state as described previously (Born et al., 2016). The athletes were asked to report any unusual and stressful events including signs of URTI immediately prior to the saliva sampling since a sympathetic stress-response would dramatically affect the concentration of cortisol, saliva flow rate and mood. In only one occasion a participant reported to be upset from such an event (i.e., a private matter that cased him stress but was not related to the study) and the sample from this particular point of measurement was excluded from the analysis.

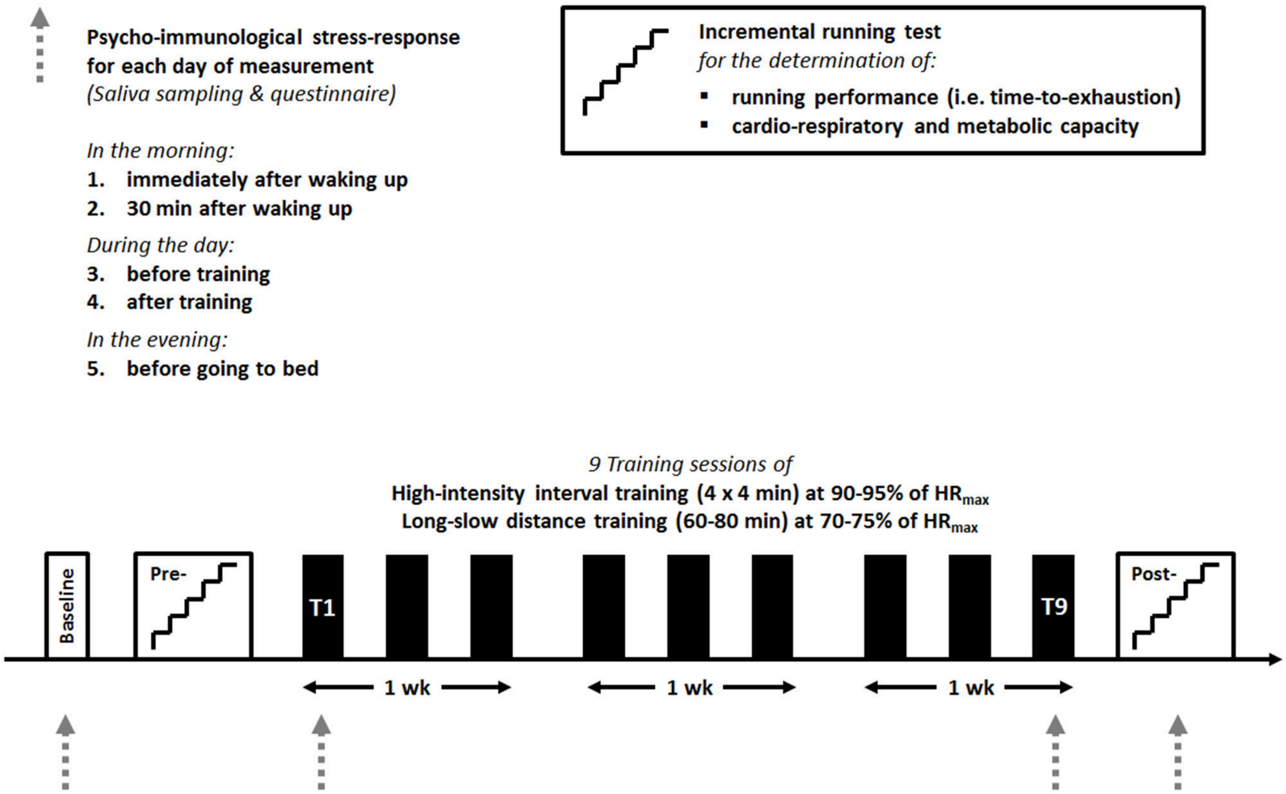

FIGURE 1 | The study design with the time-points for the saliva sampling and questionnaire on the baseline day, the first (T1) and last (T9) day of training and the follow-up for both groups.

All saliva samples were centrifuged at 2,000 g for 10 min to separate the firm mucus at the bottom of the tube. The supernatant aqueous fraction was used to analyze the concentration of cortisol and sIgA using commercially available enzyme-immunoassay kits (DRG Instruments, Marburg, Germany). The standard ranges for the determination of cortisol and sIgA were 2–80 ng/mL and 6.9–400 μg/mL with a sensitivity of 0.5 ng/mL and 0.5 μg/mL at the 95% confidence limit, respectively. The intra-assay coefficient of variation (CV) for cortisol and sIgA were 5.2 and 3.6% with an inter-assay CV of 5.7 and 5.5%, respectively. In order to cope with the inter-individual variation in the concentration of cortisol and sIgA secretion rate, the values from the baseline day were used to normalize the data.

Statistical Analysis

The data are presented as mean values ± standard deviations (SD), normal distribution was confirmed with Shapiro-Wilk's test and an alpha-level <0.05 considered as statistically significant. A 2-way analysis of variance (ANOVA) with repeated measure using Fisher's *post-hoc* test was performed to detect significant differences between the training intensity (HIIT vs. LSD) and time-points of measurement. Additionally, effect size (partial eta^2) and statistical power were calculated for each variable. As suggested previously (Pruessner et al., 2003), the area under the curve with respect to ground level (AUC_G) was determined for the psycho-immunological stress-response on each day of measurement. Pearson's product moment correlation coefficient was used to identify potential variables that were related to the change in $\dot{V}O_{2peak}$ and TTE. All data were recorded and prepared using Excel 2010 (Microsoft Corp., Redmond, USA) and analyzed subsequently with Statistical 10.0 (StatSoft Inc., Tulsa, USA).

RESULTS

Physiological Assessment

The performance data as well as cardio-respiratory and metabolic response to nine sessions of HIIT and LSD are presented in **Table 1**. While HIIT and LSD increased the TTE from Pre- to Post- ($P < 0.01$), the interaction effect revealed that the HIIT resulted in a longer TTE at Post- compared to the LSD ($P = 0.02$). The $\dot{V}O_{2peak}$ increased with the HIIT only (interaction effect, $P = 0.01$) and the levels of blood lactate concentration lessened with the LSD only (interaction effect, $P = 0.01$). The running velocities at 2 and 4 mmol/L blood lactate concentration increased with both, HIIT and LSD ($P < 0.01$ and $P < 0.01$, respectively).

Psycho-Immunological Stress-Response

Table 2 illustrates the detailed analysis of the AUC_G for the psycho-immunological stress-response during the first and last

TABLE 1 | The performance data as well as cardio-respiratory and metabolic response to nine sessions of HIIT compared to LSD (mean ± SD).

		HIIT	LSD		*F*-value	*P*-value	Partial eta^2	Test power
Time-to-exhaustion (s)	Pre-	1887 ± 290	1764 ± 221	a)	$F_{(1, 26)} = 4$	n.s.		
	Post-	2129 ± 298*+	1861 ± 220+	b)	$F_{(1, 26)} = 33$	$P < 0.01$	0.56	0.99
				c)	$F_{(1, 26)} = 6$	$P = 0.02$	0.19	0.65
Peak oxygen uptake (mL/kg/min)	Pre-	49 ± 4.5	52.4 ± 4.8	a)	$F_{(1, 26)} = 1$	n.s.		
	Post-	51.5 ± 3.9+	51.8 ± 5.3	b)	$F_{(1, 26)} = 0$	n.s.		
				c)	$F_{(1, 26)} = 8$	$P = 0.01$	0.24	0.79
Maximum heart rate (beats/min)	Pre-	196 ± 8	194 ± 8	a)	$F_{(1, 26)} = 0$	n.s.		
	Post-	194 ± 8	195 ± 8	b)	$F_{(1, 26)} = 3$	n.s.		
				c)	$F_{(1, 26)} = 4$	n.s.		
Maximum blood lactate concentration (mmol/L)	Pre-	8 ± 2.2	9.2 ± 2.1	a)	$F_{(1, 26)} = 0$	n.s.		
	Post-	8.7 ± 2.2	8.2 ± 1.7+	b)	$F_{(1, 26)} = 0$	n.s.		
				c)	$F_{(1, 26)} = 9$	$P = 0.01$	0.25	0.81
Velocity (m/s) at 2 mmol/L blood lactate concentration	Pre-	2.6 ± 0.5	2.4 ± 0.4	a)	$F_{(1, 26)} = 3$	n.s.		
	Post-	2.8 ± 0.4+	2.6 ± 0.3+	b)	$F_{(1, 26)} = 13$	$P < 0.01$	0.33	0.93
				c)	$F_{(1, 26)} = 0$	n.s.		
Velocity (m/s) at 4 mmol/L blood lactate concentration	Pre-	3.3 ± 0.4*	3 ± 0.3	a)	$F_{(1, 26)} = 8$	$P = 0.01$	0.25	0.80
	Post-	3.5 ± 0.3*+	3.1 ± 0.3+	b)	$F_{(1, 26)} = 20$	$P < 0.01$	0.44	0.99
				c)	$F_{(1, 26)} = 2$	n.s.		

Significant differences were identified with a 2-way ANOVA: training intensity (HIIT vs. LSD) x time (Pre- vs. Post-). HIIT, High-intensity training; LSD, Long-slow distance training.
a) Main effect: training intensity (HIIT vs. LSD).
b) Main effect: time (Pre- vs. Post-).
c) Interaction effect: training intensity x time.
**Significant difference compared to LSD. + significant difference compared to Pre-. n.s., not significant.*

day of training and during the follow-up. A main effect for the time was evident as the AUC_G for the levels of cortisol increased during the follow-up in both groups ($P < 0.01$). The *post-hoc* analysis revealed that, the levels of cortisol were increased from before to after exercise ($P < 0.05$) and increased compared to the corresponding values at T1 ($P < 0.05$) with both groups on the day of follow-up. The cortisol values normalized by the end of the day however, showing lower values before going to bed compared to immediately after waking up on all days of measurement (i.e., T1, T9, and follow-up) with the HIIT ($P < 0.01$) and LSD ($P < 0.01$).

A main effect for the training intensity was evident as the AUC_G for sIgA secretion rate was higher with the HIIT on T1, T9 and follow-up ($P = 0.01$). The *post-hoc* analysis showed the highest sIgA secretion rate in the morning immediately after waking up with decreasing values throughout the day in both, the HIIT ($P < 0.05$) and LSD ($P < 0.05$). The wake-up response by the end of the training period at T9 was higher with the HIIT compared to the corresponding value at T1 ($P = 0.01$) as well as compared to the LSD ($P < 0.01$; **Figure 2**). Mood remained unaffected with respect to training intensity and time.

Correlation Analysis

Person correlation analysis detected that, the increased TTE from pre- to post- correlated with the AUC_G of sIgA secretion rate on the day of follow-up ($r = 0.45$, $P = 0.02$). As well, the increase in $\dot{V}O_{2peak}$ was related to the sIgA secretion rate on day T1 ($r = 0.39$, $P = 0.04$).

DISCUSSION

The main findings of the present study were that, the HIIT results in a longer TTE and increased $\dot{V}O_{2peak}$ compared to the LSD. The ergogenic effects of HIIT were accompanied with an increased sIgA secretion rate evident as a larger AUC_G on the first and last day of training as well as follow-up. The levels of cortisol were unaffected by the training intensity (HIIT vs. LSD) but increased over time on the day of the follow-up with both, HIIT and LSD. Mood remained unaffected with both groups during the entire training period.

The results of the present study are in line with previous findings showing the benefits of HIIT to improve important variables related to the endurance performance, i.e., TTE, and $\dot{V}O_{2peak}$ (Helgerud et al., 2007; Buchheit and Laursen, 2013a,b; Ronnestad et al., 2014, 2016; Stoggl and Sperlich, 2014, 2015; Sylta et al., 2016). The research focus however was, to investigate the circadian variation of biomarkers in saliva and mood during such a period of HIIT. The question was whether the exposure to nine sessions of HIIT compared to LSD within a 3-week time frame would compromise the mucosal immune function besides the promising effects on TTE and $\dot{V}O_{2peak}$.

TABLE 2 | The AUC_G for the psycho-immunological stress-response to nine sessions of HIIT compared to LSD on the first (T1) and last (T9) day of training as well as the follow-up (mean ± SD).

		HIIT	LSD		*F*-value	*P*-value	Partial eta²	Test power
Saliva flow rate (mL/min)	T1	1476 ± 198	1346 ± 445	a)	$F_{(1, 26)} = 1$	n.s.		
	T9	1461 ± 316	1332 ± 393	b)	$F_{(1, 26)} = 7$	$P < 0.01$	0.21	0.91
	Follow-up	1225 ± 233+#	1157 ± 426	c)	$F_{(1, 26)} = 0$	n.s.		
Levels of cortisol (ng/mL)	T1	1809 ± 384	1554 ± 426	a)	$F_{(1, 26)} = 1$	n.s.		
	T9	1597 ± 565	1394 ± 257	b)	$F_{(1, 26)} = 11$	$P < 0.01$	0.3	0.99
	Follow-up	1941 ± 354#	2104 ± 855+#	c)	$F_{(1, 26)} = 2$	n.s.		
Salivary immunoglobin A secretion rate (μg/min)	T1	1917 ± 1178*	1010 ± 506	a)	$F_{(1, 26)} = 8$	$P = 0.01$	0.23	0.77
	T9	2123 ± 1394*	1142 ± 628	b)	$F_{(1, 26)} = 1$	n.s.		
	Follow-up	1968 ± 1164*	962 ± 427	c)	$F_{(1, 26)} = 0$	n.s.		
Mood (a.u.)	T1	1363 ± 204	1413 ± 150	a)	$F_{(1, 26)} = 0$	n.s.		
	T9	1391 ± 152	1444 ± 180	b)	$F_{(1, 26)} = 2$	n.s.		
	Follow-up	1465 ± 164	1420 ± 92	c)	$F_{(1, 26)} = 3$	n.s.		

Significant differences were identified with a 2-way ANOVA with repeated measure: training intensity (HIIT vs. LSD) x time (T1 vs. T9 vs. Follow-up).
a) Main effect: training intensity (HIIT vs. LSD).
b) Main effect: time (T1 vs. T9 vs. Follow-up).
c) Interaction effect: training intensity x time.
**Significant difference compared to LSD.*
+ Significant difference compared to T1.
 # Significant difference compared to T9.
n.s., Not significant.

In contrast to the initial hypothesis and the general assumption that chronic exposure to high training loads compromises the mucosal immune function evident as a decreased sIgA secretion rate (Tiollier et al., 2005; Trochimiak and Hubner-Wozniak, 2012) the HIIT in the present investigation actually increased the sIgA secretion rate throughout the entire training period. An earlier review concluded that extreme efforts, such as HIIT, would increase the infection risk of the upper-respiratory tract while moderate intensity exercise, such as LSD, would improve the mucosal immune function (Trochimiak and Hubner-Wozniak, 2012). A "J"-shaped relationship was generally accepted between the immune function and the training load, while both, too low as well as too high training loads, would impair the immune function (Trochimiak and Hubner-Wozniak, 2012). The latter assumption however presumes that the mucosal immune system needs to be stressed in some way to adapt and improve its capacity to neutralize and defend viral pathogens in a similar way as muscles becomes stronger when exposed to regular training stress and adequate overload.

The question arises, how much training and overload is necessary to improve the mucosal immune function. In the present study, the stimulus of nine sessions of HIIT followed by at least 1 day of recovery was adequate to increase the number of antimicrobial proteins in the saliva as indicated by an elevated sIgA secretion rate. In contrast, the LSD did not provide a sufficient stimulus to adapt and augment the mucosal immune function evident as a sIgA secretion rate that was unaltered over the time course of the training period.

From a mechanistic perspective, the sIgA is one of the most abundant antimicrobial proteins in the saliva (Papacosta and Nassis, 2011) and synthesized locally in the submucosa (Allgrove et al., 2008). The activation of the sympathetic nervous system and hypothalamic-pituitary-adrenal-axis promotes the transepithelial transport of sIgA to the mucosal surface (Goodrich and McGee, 1998). Especially the sIgA secretion rate increased acutely immediately after a bout of high-intensity exercise (Allgrove et al., 2008). The concentration of salivary cortisol however did not respond until 1 h after exercise (Allgrove et al., 2008) explaining why the cortisol response remained unaffected in the present study taking the saliva samples immediately after the HIIT and LSD. While the sIgA secretion rate responded immediately to the increased stress of HIIT, sIgA could therefore be a marker of stress being more sensitive than salivary cortisol.

The question remains, whether the increased sIgA secretion rate when waking up on T9 with the HIIT shows the stress response from the previous training session, which was still evident during recovery, or if the increased sIgA secretion rate indicates a chronically enhanced mucosal immune function. In both cases, with the repeated exposure to high training loads (nine sessions of HIIT) the enhanced secretion of sIgA must be matched by an increased synthesis in the submucosal plasma cells (Goodrich and McGee, 1998). Otherwise, over the time course of nine HIIT sessions the store of IgA in the submucosa available for transport across the epithelium would become depleted (Proctor et al., 2003). The lack of any peak elevation of sIgA with the LSD indicates that the more intense training stimulus with the

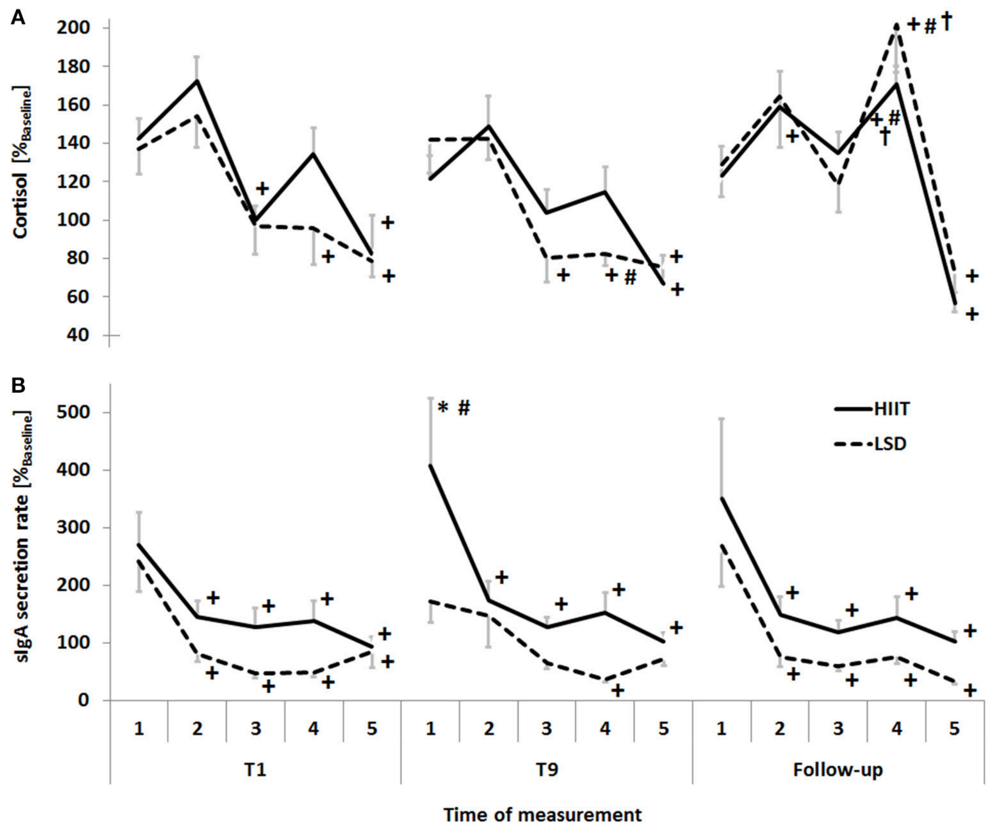

FIGURE 2 | The circadian variation of the **(A)** levels of cortisol and **(B)** salivary immunoglobin A (sIgA) secretion rate in response to the high-intensity interval training (HIIT) and the long-slow distance training (LSD) normalized to the concentrations obtained from the baseline day before the start of the training period. Samples were taken on the first (T1) and ninth (T9) day of training as well as the follow-up (1) immediately after waking up, (2) 30 min after waking up, (3) before training, (4) after training and (5) before going to bed. For the sake of clarity, the standard error is illustrated for the corresponding mean values. Significant differences are indicated as follows: * between groups, + in comparison to immediately after waking up of the same day, # in comparison to the corresponding value on day T1, † in comparison to before exercise.

HIIT must has induced functional adaptation that elevated the sIgA synthesis and augmented the mucosal immune function in addition to the ergogenic effects of a longer TTE and increased $\dot{V}O_{2peak}$.

Recently, particular interest has been drawn to the correlation of reduced sIgA secretion rate and increased risk of URTI. During polarized endurance training including both, continuous and interval training, the runners who showed greater basal sIgA concentrations suffered less from URTI. Interestingly, the sIgA concentration before the start of the study predicted the number of sick-days ($r = -0.76$, $P < 0.01$) during the following 12-week training period (Ihalainen et al., 2016). The aforementioned findings indicate that the mucosal immune function might be predisposed by either genetic factors or affected by the individual's training history. The findings of the present study support the latter by showing an increased sIgA secretion rate in response to the more severe training stress of the HIIT compared to the moderate intensity exercise with the LSD.

Therefore, the generally accepted "J"-shaped relationship between training load and the risk of URTI needs to be questioned. In a recent review Walsh and Oliver (2016) discussed this matter based on the current literature and concluded "*that international athletes performing high-volume training suffer fewer, not greater, URTI episodes than lower-level performers*". The authors also concluded that the immune function is actually improved with the regular but intermittent exposure to various forms of stress (Walsh and Oliver, 2016). Linked with the results of the present study it might be time to consider the mucosal immune function as a highly adaptable system that, at least in a 3-week time period, responds well to the stress of HIIT.

In the present investigation, salivary cortisol remained unaffected immediately after exercise on the first and last day of training with both training groups. During the day of the follow-up however the incremental exercise test to exhaustion increased the levels of cortisol immediately after exercise with both, the HIIT and LSD. Investigations evidenced that the participation in official competitions induced greater levels of cortisol compared to training matches or race simulations indicating that the psychological stress itself rather than the actual physical load affects the response in cortisol (Rohleder et al., 2007; Moreira et al., 2012a,b, 2013). When comparing two volleyball matches that were played against the same opponent, the more important final championship match induced a greater cortisol response compared to the regular season match (Moreira et al., 2013). Similarly, in elite basketball players the cortisol values were still elevated largely above baseline during the competition phase even with a physical load that was almost half as much as during the preceding training phase (He et al., 2010). In the present study, the incremental exercise test that was performed on the day of the follow-up created a semi-competitive situation since each runner attempted to compel themselves mentally and physically as hard as possible in order to profit from the past training period and outrun their training colleagues. The arousal, anxiety, and pressure to perform well during this type of performance test seemed to induce a substantial cortisol response which was not evident at any time point during the training phase neither with the HIIT nor LSD.

Recent studies showed that the compromised mucosal immune function, i.e., reduced sIgA secretion rate, induced by the stress of competition was accompanied with high levels of cortisol (He et al., 2010; Moreira et al., 2013). Therefore, an antagonistic activity of increased cortisol values that inhibit the sIgA response has been discussed (He et al., 2010). In the present study, especially the HIIT required the runners to perform each training session close to their physical limit at 90–95% of HR_{max}. The mood data however show, that our athletes did not feel pressured or psychologically stressed due to the high training loads of HIIT shown by a mood state that was not different to the LSD. Also the levels of cortisol on the first and last day of training were fairly low with the HIIT and not different to LSD. Assuming an antagonistic activity of cortisol and sIgA (He et al., 2010; Moreira et al., 2013), the low levels of cortisol on the first and last day of training could explain why our athletes did not show any reduced sIgA secretion rate with the HIIT but adapted to the training stress and improved their mucosal immune function.

CONCLUSION

In contrast to the hypothesis, we could not investigate any signs of a compromised mucosal immune function with the HIIT compared to LSD. The ergogenic effects of HIIT, i.e., increased $\dot{V}O_{2peak}$, were even accompanied with an increased sIgA secretion rate indicating that the mucosal immune system adapted over the time course of the training period by increasing the number of antimicrobial proteins and improving the capacity to neutralize and defend viral pathogens. The training stimulus of the LSD on the other hand was insufficient to improve the mucosal immune function or $\dot{V}O_{2peak}$. Based on our data we cannot generally accept the assumption that high training loads necessarily compromises the mucosal immune function. Connecting the data of the present study with previous findings (Born et al., 2016; Walsh and Oliver, 2016), it might be time to consider the mucosal immune function as a highly adaptable system that responds well to the stress and load of training, in particular nine sessions of HIIT within 3 weeks.

The HIIT had no effect on the levels of cortisol and mood. Therefore, the psychological stress, i.e., the arousal, anxiety, mental stress, and pressure to perform well during competition (Rohleder et al., 2007; Moreira et al., 2012a,b, 2013), rather than the actual physical load of exercise might be responsible for an impaired mucosal immune function. Future studies should apply the circadian variation of sIgA secretion rate, cortisol and mood to further distinguish between the psychological and physical stressors and how both could impact the mucosal immune function during periods with an intensified training load and competition.

AUTHOR CONTRIBUTIONS

Conception of the experimental design, data collection, analysis, interpretation, preparing and critically revising the manuscript: DB, CZ, and BS. All authors read and approved the final version of the manuscript.

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No Additional Benefits of Block- Over Evenly-Distributed High-Intensity Interval Training within a Polarized Microcycle

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Introduction: The current study aimed to investigate the responses to block- versus evenly-distributed high-intensity interval training (HIT) within a polarized microcycle.

Methods: Twenty well-trained junior cross-country skiers (10 males, age 17.6 ± 1.5 and 10 females, age 17.3 ± 1.5) completed two, 3-week periods of training (EVEN and BLOCK) in a randomized, crossover-design study. In EVEN, 3 HIT sessions (5 × 4-min of diagonal-stride roller-skiing) were completed at a maximal sustainable intensity each week while low-intensity training (LIT) was distributed evenly around the HIT. In BLOCK, the same 9 HIT sessions were completed in the second week while only LIT was completed in the first and third weeks. Heart rate (HR), session ratings of perceived exertion (sRPE), and perceived recovery (pREC) were recorded for all HIT and LIT sessions, while distance covered was recorded for each HIT interval. The recovery-stress questionnaire for athletes (RESTQ-Sport) was completed weekly. Before and after EVEN and BLOCK, resting saliva and muscle samples were collected and an incremental test and 600-m time-trial (TT) were completed.

Results: Pre- to post-testing revealed no significant differences between EVEN and BLOCK for changes in resting salivary cortisol, testosterone, or IgA, or for changes in muscle capillary density, fiber area, fiber composition, enzyme activity (CS, HAD, and PFK) or the protein content of VEGF or PGC-1α. Neither were any differences observed in the changes in skiing economy, $\dot{V}O_2max$ or 600-m time-trial performance between interventions. These findings were coupled with no significant differences between EVEN and BLOCK for distance covered during HIT, summated HR zone scores, total sRPE training load, overall pREC or overall recovery-stress state. However, 600-m TT performance improved from pre- to post-training, irrespective of intervention ($P = 0.003$), and a number of hormonal and muscle biopsy markers were also significantly altered post-training ($P < 0.05$).

Discussion: The current study shows that well-trained junior cross-country skiers are able to complete 9 HIT sessions within 1 week without compromising total work done

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and without experiencing greater stress or reduced recovery over a 3-week polarized microcycle. However, the findings do not support block-distributed HIT as a superior method to a more even distribution of HIT in terms of enhancing physiological or performance adaptions.

Keywords: cross-country skiing, endurance, junior athletes, muscle, periodization, recovery, stress, training load

INTRODUCTION

Various theories pertaining to training periodization (i.e., the division of an athlete's seasonal training into smaller units and periods of time) have been discussed in the scientific literature (see Issurin, 2010 for a comprehensive review). However, these theories have been criticized for lacking an evidence base (Kiely, 2012), which seems to be due, at least in part, to the logistical challenges associated with comparing different forms of training within athlete groups. In one study that reported the effects of two different training periodization models used over two seasons with elite kayakers (García-Pallarés et al., 2010), rigorous scientific control was limited due to the applied and longitudinal nature of the study. The outcomes of group studies are further complicated by the variability of individual responses to long-term training programs (Mann et al., 2014). On the other hand, case studies of effective organizational strategies over seasonal periods (e.g., Støren et al., 2012) provide limited support for general use.

Experimental studies designed to investigate the effects of different training organization models on physiological and performance adaptations are typically limited to short intervention periods. This results in a need for potent training stimuli, particularly where athlete populations are concerned. One such method used to develop aerobic power and performance has been to concentrate a large number of high-intensity interval training (HIT) sessions (e.g., 5–15 sessions) into a short period of time (e.g., 6–14 days) (Stølen et al., 2005; Breil et al., 2010; Wahl et al., 2013, 2014; Rønnestad et al., 2014b, 2016). This strategy has been referred to as "block training" and is based on the overload principle, with a super-compensation in selected fitness components thought to occur after a period of focused loading followed by a short recovery period (Issurin, 2010).

While HIT is considered necessary to elicit physiological and performance gains among endurance-trained athletes (Laursen et al., 2002; Iaia et al., 2009; Buchheit and Laursen, 2013a,b; Gunnarsson et al., 2013), low-intensity training (LIT) remains a fundamental component of endurance programs (Sandbakk and Holmberg, 2014). Combining these two forms of contrasting training stimuli, while performing relatively little moderate-intensity training (MIT), is referred to as polarized training (Seiler and Kjerland, 2006; Laursen, 2010). Some studies have suggested that more polarized training distributions are beneficial to endurance performance (Esteve-Lanao et al., 2007; Neal et al., 2012; Stöggl and Sperlich, 2014). Moreover, two recent studies have demonstrated improvements in $\dot{V}O_2$max, maximal power output (MPO) and power output at blood lactate concentrations of 2–4 mmol·L^{-1} among cyclists and cross-country skiers following a period of block-distributed polarized training (i.e., a series of concentrated HIT sessions followed by LIT), but not after a more traditional (even) distribution of LIT and HIT (Rønnestad et al., 2014b, 2016).

Despite these positive findings associated with blocking HIT, prescribing short periods of intensified training in this manner has also been shown to result in the development of overreaching (OR) symptoms. For example, Halson et al. (2002) showed that 2 weeks of intensified HIT in the middle of a 6-week training period led to OR among trained cyclists, reporting reductions in MPO, maximal heart rate (HR_{max}), $\dot{V}O_2$max and cycling performance, as well as increases in global mood disturbance. In addition, Jürimäe et al. (2004) observed reductions in performance capacity, resting testosterone levels and recovery, as well as increases in stress levels, following 6 days of intensified training with trained rowers. Although block HIT studies have not typically monitored subjective markers of well-being, these findings highlight the importance of understanding the multi-dimensional responses to intense training interventions, especially given the potential for short-term OR to develop into the more chronic overtraining syndrome (Meeusen et al., 2013).

At present there is a lack of information regarding the physiological, psychological and performance-based responses of junior athletes performing block HIT, which would be relevant to coaches working in a variety of endurance sports. Therefore, the present investigation was designed to compare the effects of two polarized training interventions in well-trained junior male and female cross-country skiers. Nine HIT sessions were concentrated in the middle of a 3-week training period in the experimental intervention (BLOCK), while the same 9 HIT sessions were distributed evenly over the 3-week period in the control intervention (EVEN). Supplementary LIT and strength training were also matched across the two interventions, with only the organization of sessions differing. It was hypothesized that BLOCK would lead to a greater relative increase in $\dot{V}O_2$max and 600-m time-trial (TT) performance compared with EVEN, despite covering less distance during the HIT sessions and attaining lower heart rates (HRs) during BLOCK compared with EVEN. Higher perceived exertion and stress, as well as reduced perceived recovery, were also expected during BLOCK compared with EVEN.

MATERIALS AND METHODS

Participants

Twenty well-trained cross-country skiers (10 males: age 17.6 ± 1.5 years, body mass 72.3 ± 4.8 kg, $\dot{V}O_2$max 67.1 ± 2.6 mL·kg^{-1}·min^{-1}; 10 females: age 17.3 ± 1.5 years, body mass 61.1 ± 7.5 kg, $\dot{V}O_2$max 54.2 ± 4.0 mL·kg^{-1}·min^{-1}) were recruited from two specialist Swedish ski schools. All participants had at least 6 years of experience racing in cross-country skiing and competed at a national level, while eight were also members of national junior development teams. Average endurance training volume was typically 500–750 h per year, or 9–14 h per week, and an additional 60–80 h of functional strength training was completed annually. Weekly training frequency was periodized, with 4–5 endurance sessions (6–8 h) completed per week during low volume periods and up to 12 endurance sessions (25 h) completed per week during high volume periods. After being informed of the aims and possible risks of the study the participants provided written informed consent to take part and informed parental consent was obtained for those aged under 18 years. The study was pre-approved by the Regional Ethical Review Board, Umeå University, Umeå, Sweden.

Study Overview

The study was conducted at the end of the cross-country ski racing season, from April to June. A crossover design was used, whereby one group of athletes (EVEN-BLOCK; 6 males and 7 females) completed 3 weeks of EVEN followed by 3 weeks of BLOCK, separated by a 4-day break, and the other group (BLOCK-EVEN; 4 males and 3 females) completed 3 weeks of BLOCK followed by 3 weeks of EVEN, also separated by a 4-day break (**Table 1**). As such, all 20 athletes performed both training interventions. The number of athletes in each group was not equal for the logistical reason that all HIT sessions needed to be completed on the same hill. Laboratory-based testing was carried out before and after the two interventions.

Pre- and Post-testing

All participants attended the laboratory once during each test period to provide a resting saliva sample and to complete the 76-question recovery-stress questionnaire for athletes (RESTQ-Sport), as well as sub-maximal and maximal incremental tests and a 600-m TT (**Figure 1**). Participants were familiar with the sub-maximal and maximal treadmill protocols, having completed them routinely as part of their seasonal testing. The specific 600-m TT protocol was new to all participants, so a familiarization was included in the test battery. Participants arrived at the laboratory in a rested state having consumed a standardized breakfast. The sub-maximal and maximal incremental tests, as well as a familiarization to the 600-m TT, were completed in the morning prior to a standardized lunch, while the 600-m TT was completed after lunch. In addition to the main test day, muscle biopsies were taken on a separate day during each test period from a sub-group of 11 athletes aged 18 years and over (6 males: age 18.7 ± 0.8 years; 5 females: age 18.6 ± 0.9 years).

Saliva Samples

Resting saliva samples were collected by passive drool (Beaven et al., 2008) on arrival at the laboratory, between 08:00–08:30 during each test period. The participants consumed only water in the 1 h prior to collection (Sperlich et al., 2012). Samples were collected in sterile tubes and stored at −20°C until analysis. After thawing and centrifuging at 2,000 rpm for 10 min, the samples were analyzed in duplicate and average values were used to determine cortisol, testosterone and immunoglobulin A (IgA) concentrations using commercial ELISA kits (Salimetrics LLC, Pennsylvania, USA), as described by Beaven et al. (2008).

RESTQ-Sport

The RESTQ-Sport was completed on arrival at the laboratory after providing a saliva sample. The questionnaire consists of 12 general scales and 7 additional sport-specific scales, with 4 questions per scale, and assesses the balance between perceived recovery and stress (Kellmann and Kallus, 2001). The total stress score corresponds to the sum of the scores of all of the stress subscales (7 general plus 3 sport-specific), while the total recovery score represents the sum of the scores of all of the recovery subscales (5 general plus 4 sport-specific). A general indicator of recovery-stress was calculated as the total recovery minus the total stress score (Kellmann and Kallus, 2001).

Sub-maximal and Maximal Incremental Tests

Following the measurement of height and body mass (Seca 764, Hamburg, Germany), sub-maximal and maximal incremental tests were carried out on a motor-driven treadmill (Rodby RL 3000, Rodby, Vänge, Sweden) according to procedures previously described by McGawley and Holmberg (2014). Briefly, the diagonal roller-skiing technique and the same pair of pre-warmed roller-skis (Pro-Ski Classic C2, Sterners, Dala-Järna, Sweden) were used for both tests. The sub-maximal test was fixed at a 7° gradient and included a 4-min warm-up followed by four, 4-min continuous stages. Speeds differed for individuals depending on age, sex, and skiing ability, with the warm-up and first stage completed at 5.2–7.0 km/h and increases of either 0.8 or 1.0 km/h per stage to final speeds of 7.6–10.0 km/h. At the end of the sub-maximal test there was a 1-min break before participants commenced the maximal test. Depending on age, sex, and ability, the starting speed for the maximal test was 10, 11, or 12 km/h and the initial gradient was 3° or 4°. The gradient was then increased by 1° every minute, up to a maximum of 9°, after which speed was increased by 0.4 km/h every minute. The test was terminated when participants were unable to continue. Respiratory variables were measured using a mixed expired air procedure with an ergospirometry system (AMIS 2001 model C, Innovision A/S, Odense, Denmark) equipped with a flow meter. The gas analysers were calibrated with a high-precision mixture of 16.0% O_2 and 4.0% CO_2 (Air Liquide, Kungsängen, Sweden) and the flow meter was calibrated at three rates with a 3-L air syringe (Hans Rudolph, Kansas City, USA). The $\dot{V}O_2$ values were calculated from 10-s epochs and skiing economy is expressed as the 1-min steady-state value measured during the final minute of the second sub-maximal stage, while $\dot{V}O_2max$ is expressed as the highest 30-s average recorded over any three consecutive 10-s samples (i.e., a sliding average).

600-m Time-Trial

A familiarization to the 600-m TT, which was limited to 400 m in order to minimize any impact of fatigue, was carried out on the same morning as the sub-maximal and maximal incremental tests, after at least 1 h of rest. The 600-m TT was then completed in the afternoon, following a standardized lunch and at least 2 h of rest, again according to the methods described by McGawley

TABLE 1 | An overview of the 53-day crossover study design incorporating two, 3-week training interventions (EVEN and BLOCK) flanked by pre- and post-testing.

	Day				
Group	**1–3**	**4–24**	**25–28**	**29–49**	**50–53**
EVEN-BLOCK ($n = 13$)	Test period 1	3-week EVEN	Test period 2	3-week BLOCK	Test period 3
BLOCK-EVEN ($n = 7$)		3-week BLOCK		3-week EVEN	

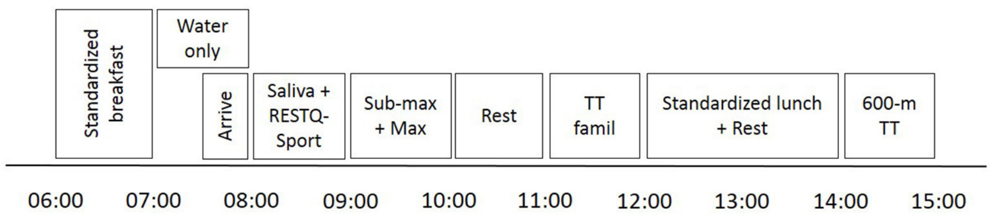

FIGURE 1 | A schematic of the laboratory tests performed before and after the training interventions. RESTQ-Sport: 76-question recovery-stress questionnaire for athletes; Sub-max + Max: sub-maximal and maximal incremental tests; TT famil: 400-m familiarization to the 600-m time-trial (TT).

and Holmberg (2014). Following a 15-min warm-up the test protocol began with 100 m at a fixed speed (8.8 km·h^{-1} for the females and 10.8 km·h^{-1} for the males) to avoid over-pacing, followed by a self-paced maximal effort for the remaining 500 m. The treadmill gradient was fixed at 7° and the diagonal-stride technique was used throughout. The same motor-driven treadmill as that described in Section Sub-maximal and Maximal Incremental Tests was used, fitted with lasers that automatically increased or decreased the speed if the athlete moved to the front or rear of the belt, respectively, maintaining a constant speed otherwise (Swarén et al., 2013). Expired air was collected throughout using the procedures described above.

Muscle Biopsies

Resting muscle biopsies were taken from the vastus lateralis 1–3 days before the main test day during each of the three test periods (see **Table 1**). After 10 min of supine rest the skin above the middle portion of the vastus lateralis was anesthetized with 2% lidocaine (B. Braun Medical, Danderyd, Sweden) and biopsies were taken using the needle technique with suction enhancement (Bergström, 1962; Hennessey et al., 1997). The tissue obtained was rapidly cleaned from blood and fat and divided into three parts. One part was mounted in an embedding medium (Tissue Tek® O.C.T. Compound) for subsequent histochemical analyses and frozen immediately in isopentane that was cooled to its freezing point in liquid nitrogen. The other two parts were immediately frozen in liquid nitrogen for subsequent enzyme and protein-content analyses. The samples were stored at −80°C until analyzed. For histochemical analysis, serial 10-µm cross-sections were cut in a cryostat at −20°C. Following preincubation at pH 4.3, 4.6, and 10.3, the sections were stained for myofibrillar ATPase at pH 9.4 and the muscle fibers were classified as type I, IIA, IIB, or IIC (Brooke and Kaiser, 1969). To visualize capillaries, the cross-sections were stained by the amylase-PAS procedure (Andersen, 1975). Computer image analysis (Leica QWin Runner V 3.5.1, Leica Microsystems, Bromma, Sweden) was performed to evaluate capillary density, fiber composition and fiber areas, as described by Kazior et al. (2016). Maximal enzyme activities of citrate synthase (CS), 3-hydroxyacyl CoA dehydrogenase (HAD) and phosphofructokinase (PFK) were carried out according to the procedures described by Opie and Newsholme (1967), Essén et al. (1975), Alp et al. (1976), respectively. The protein content of VEGF and PGC-1α were measured using western blots. Briefly, 20 mg of tissue was homogenized in 250 µl of RIPA buffer (Sigma) using glass/teflon homogenization. Following centrifugation at 13,000 g, total protein concentration of the supernatant was estimated using the PierceTM BCA Protein Assay kit (Thermo Fisher Scientific). Protein (25 µg) was separated by SDS-PAGE (NuPAGE® Bis-Tris Precast Gels, 4–12%), transferred to nitrocellulose membranes and detection was made using SuperSignalWestPico Chemiluminescent Substrate (Thermo Fisher Scientific). Antibodies used were Anti-PGC-1α Mouse mAb (4C1.3) (ST1202) and Anti-VEGF (Ab-3) Mouse mAb (14–124) (GF25) (Merck Millipore). Results are presented as ratios of VEGF or PGC-1α expression to a loading control, beta Actin (ab8227) (Abcam), ensuring equal loading on the gel (Ruas et al., 2012; Andrzejewski et al., 2015). Also, gel-to-gel variation was adjusted for using an internal standard.

Training

EVEN and BLOCK Interventions

The two, 3-week training interventions were developed in close cooperation with the coaches of the participating athletes. The EVEN intervention replicated a typical 3-week polarized training cycle, while BLOCK involved 1 week of LIT only, both before and after an intensified week of HIT only. The EVEN and BLOCK interventions were workload matched and included 7 and 9 LIT sessions, respectively (matched for total training time), as well as 9 HIT sessions and 6 functional strength sessions (**Table 2**).

TABLE 2 | The number and distribution of low-intensity training (LIT), high-intensity interval training (HIT) and functional strength (STR) training sessions during three weeks of evenly-distributed (EVEN) and block (BLOCK) training.

	EVEN			BLOCK		
	Week 1	Week 2	Week 3	Week 1	Week 2	Week 3
LIT	2	3	2	4	0	5
HIT	3	3	3	0	9	0
STR	2	2	2	3	0	3

Durations of the LIT sessions ranged from 58 ± 4 to 127 ± 11 min (∼60-, 90-, 105-, or 120-min sessions) and were completed at ∼60–80% of HR_{max} as either skiing (∼60% of all sessions, either roller- or on-snow skiing, depending on weather conditions), running (∼35% of all sessions) or cycling (∼5% of all sessions). The distribution of different LIT activities was similar between the two interventions. The HIT sessions were standardized at 75 min and consisted of a warm-up, 5 × 4-min intervals separated by 6 min of active recovery and a warm-down. The intervals were completed using the diagonal-stride cross-country skiing technique on the same pair of roller-skis throughout the study for each individual. The aim was to cover as much total distance as possible, as evenly as possible, over the five intervals within each session. Distance covered was measured to the nearest meter for all athletes during each interval for every HIT session. All intervals were completed on the same uphill asphalt slope (∼12%/7°) and the active recovery involved a downhill jog back to the start. In the case of a problem with the roller-skis participants completed the session by running on the same uphill slope with poles (distance covered was not analyzed for running intervals). All HIT sessions were performed in groups of 6–8 athletes supervised by at least two researchers and one coach. A standardized 20-min warm-up, including a 2-min uphill interval on the training hill, was performed before each HIT session and a 15-min cool-down was performed afterwards. The 9 HIT sessions in week 2 of BLOCK were organized such that 2 sessions were completed on days 1, 2, and 5 (separated by at least 5 h of rest and a meal), 1 session was completed on days 3, 6, and 7, leaving day 4 as a rest day. The strength sessions completed throughout the study involved functional and complex exercises and were supervised as part of the athletes' regular training program.

Training Loads

Heart rate was monitored for all LIT and HIT training sessions (Polar RS800CX, Polar Electro Oy, Kempele, Finland) and data were subsequently analyzed for the determination of average HR (HR_{av}), HR_{max}, session duration and time spent in each of the HR zones. The summated HR zone (sHRZ) method was used to quantify the HR-based training load for each session using the following five HR zones: 1 = 50–60% of HR_{max}, 2 = 60–70% of HR_{max}, 3 = 70–80% of HR_{max}, 4 = 80–90% of HR_{max} and 5 = 90–100% of HR_{max} (Edwards, 1993; Foster et al., 2001). Cumulated time spent in each zone (in min) was multiplied by the zone value (i.e., 1–5) to obtain an overall sHRZ training load. The second approach to quantifying training load used a modification of the 0–10 category ratio rating scale (CR-10) originally presented by Borg (1982). As described by Foster et al. (2001), within 30 min after every training session participants responded to the simple question "How was your workout?" using a 10-point scale, with 0 and 10 corresponding to "rest" and "maximal," respectively. The text on the scale was presented to the athletes in both English and Swedish. The session rating of perceived exertion (sRPE) training load was calculated by multiplying the 0–10 rating by the total session duration (in min) and expressed in arbitrary units (Foster et al., 2001). Total sRPE training load scores were calculated for each individual by summing the sRPE training loads for all LIT and HIT sessions during EVEN and BLOCK.

Recovery and Stress Measures

Following the warm-up prior to all LIT and HIT training sessions the participants reported their perceived recovery (pREC) on a scale from 0 to 10, with 0 and 10 corresponding to "very poorly recovered/extremely tired" and "very well recovered/highly energetic," respectively (Laurent et al., 2011). The RESTQ-Sport was completed weekly on a rest day prior to starting each training week at a standardized time of day.

Data Analysis

The Statistical Package for the Social Sciences (SPSS, Version 22) was used to carry out statistical analyses. Interval and ratio data are expressed as mean ± standard deviation, while ordinal data (sRPE, pREC, and RESTQ-Sport) are expressed as median [range]. Paired *t*-tests were used to compare responses to HIT versus LIT and EVEN vs. BLOCK, while unpaired *t*-tests were used to compare responses between males and females. Two-way ANOVAs with repeated measures were used to identify the intervention (EVEN vs. BLOCK), time (pre- to post-training) and interaction effects. The magnitude of the training effect for EVEN vs. BLOCK was also assessed using effect size (ES), where differences of <0.2, <0.6, <1.2, and <2.0 are interpreted as trivial, small, moderate and large, respectively (Hopkins et al., 2009). For the interval and ratio data, two-way ANOVAs with *post-hoc* Tukey tests were used to identify interaction effects and differences between the interventions (EVEN vs. BLOCK) and training weeks and HR zones. For the ordinal data, Friedman tests were used to compare weeks within each intervention and Wilcoxon signed rank tests were used to compare pairwise responses to HIT versus LIT and EVEN versus BLOCK, while Mann-Whitney tests were used to compare responses between males and females. The level of statistical significance was set at $P < 0.05$.

RESULTS

Changes from Pre- to Post-training

Pre- to post-training effects of EVEN and BLOCK are displayed in **Table 3**. There were no interaction effects between intervention and time for any of the performance, saliva or muscle biopsy variables, as demonstrated by the change (Δ) data ($P > 0.05$). Neither were there any significant intervention (group) effects ($P > 0.05$). However, there were significant

TABLE 3 | Mean ± SD pre- to post-training and change (Δ) data following three weeks of evenly-distributed (EVEN) or block (BLOCK) training.

	EVEN			BLOCK			Δ	
	Pre	Post	Δ	Pre	Post	Δ	*P*-value	ES
***n* = 20**								
Skiing economy (O_2 L·min^{-1})	2.83 ± 0.57	2.78 ± 0.57*	−0.06 ± 0.10	2.77 ± 0.58	2.79 ± 0.58	0.02 ± 0.16	0.117	0.79
VO_2max(mL·kg^{-1}· min^{-1})	60.3 ± 7.2	61.2 ± 7.9	0.9 ± 2.6	61.4 ± 8.1	60.6 ± 8.2	−0.8 ± 2.4	0.071	0.67
600-m time-trial (s)^T	187 ± 23	183 ± 25*	−3 ± 5	185 ± 23	184 ± 22	−1 ± 6	0.280	0.44
Resting cortisol (μg/dL)	0.45 ± 0.21	0.54 ± 0.30	0.09 ± 0.21	0.53 ± 0.32	0.48 ± 0.19	−0.05 ± 0.30	0.208	0.59
Resting testosterone (pg/mL)^T	108 ± 75	96 ± 45	−12 ± 51	108 ± 53	86 ± 39	−20 ± 41	0.592	0.15
Resting testosterone:cortisol^T	264 ± 203	216 ± 157	−48 ± 94	257 ± 190	218 ± 170	−39 ± 139	0.817	0.18
Resting IgA (μg/mL)	36 ± 34	76 ± 83	40 ± 96	72 ± 83	45 ± 43	−26 ± 69	0.081	0.68
***n* = 11**								
Capillary density (per mm^2)	377 ± 31	379 ± 44	3 ± 34	385 ± 42	365 ± 36	−20 ± 39	0.253	0.66
Mean fiber area (μm^2)^T	4594 ± 761	4661 ± 764	68 ± 522	4596 ± 776	4968 ± 1000	372 ± 655	0.379	0.11
Type I (%)	66.2 ± 7.5	69.1 ± 6.7	2.9 ± 6.5	67.5 ± 6.5	67.2 ± 8.3	−0.3 ± 7.4	0.203	0.50
Type IIA (%)	25.2 ± 6.4	22.7 ± 5.6	−2.5 ± 4.8	24.1 ± 5.0	21.9 ± 7.9	−2.2 ± 8.3	0.904	0.07
Type IIB (%)	7.2 ± 4.1	7.2 ± 3.8	0.0 ± 3.2	7.5 ± 4.4	9.4 ± 5.9	1.9 ± 3.9	0.177	0.60
Type IIC (%)	1.4 ± 1.9	1.0 ± 2.4	−0.4 ± 3.4	1.0 ± 2.4	1.5 ± 2.6	0.5 ± 3.9	0.680	0.27
CS activity (μmol/min/g)	23.2 ± 2.9	22.5 ± 2.9	−0.7 ± 2.5	23.6 ± 2.7	22.5 ± 1.7	−1.1 ± 2.1	0.743	0.15
HAD activity (μmol/min/g)^T	7.4 ± 1.0	7.4 ± 1.1	0.0 ± 1.1	7.6 ± 1.1	6.9 ± 0.9*	−0.7 ± 1.0	0.317	0.60
PFK activity (μmol/min/g)^T	21.7 ± 2.9	20.7 ± 2.1	−1.0 ± 2.3	20.8 ± 2.1	20.1 ± 2.4	−0.7 ± 1.9	0.753	0.14
VEGF protein content (AU)	20.0 ± 9.3	15.4 ± 10.7	−4.7 ± 15.2	16.5 ± 10.9	19.9 ± 15.5	3.5 ± 12.4	0.235	0.53
PGC-1α protein content (AU)^T	0.07 ± 0.02	0.09 ± 0.02*	0.02 ± 0.02	0.08 ± 0.01	0.11 ± 0.04*	0.03 ± 0.04	0.862	0.11

*CS, Citrate synthase; HAD, 3-hydroxyacyl CoA dehydrogenase; PFK, phosphofructokinase; AU, arbitrary units. ^{T}Significant time (pre- to post-training) effect, irrespective of intervention ($P < 0.05$); *Significantly different from pre-training ($P < 0.05$).*

time (i.e., pre- to post-training) effects, irrespective of group, for 600-m TT performance, resting testosterone concentration and testosterone:cortisol ratio, mean muscle fiber area, HAD and PFK activity and PGC-1α protein content.

Adherence to Training

In total the athletes completed 97 ± 6% (range: 90–100%) of the HIT sessions during EVEN and all (i.e., 100 ± 0%) of the HIT sessions during BLOCK and 91 and 99% of these sessions, respectively, were performed using diagonal roller-skiing. A total of 95 ± 4% (range: 90–100%) and 98 ± 4% (range: 90–100%) of the LIT sessions were completed during EVEN and BLOCK, respectively.

Responses to Training: LIT vs. HIT

A description of the HR and sRPE responses during LIT and HIT for EVEN and BLOCK combined (i.e., independent of intervention type) is presented in **Table 4** for all participants, and for males and females separately.

Responses to Training: Even vs. Block

Training Time for LIT

The LIT durations for the three separate weeks differed during EVEN and BLOCK (**Table 5**), while total time spent performing LIT did not differ between the two interventions (742 ± 33 and 754 ± 28 min for EVEN and BLOCK, respectively; $P = 0.218$).

Performance during HIT

Average distances covered during each of the 5 × 4-min intervals were similar during EVEN and BLOCK and are presented in **Table 6** for all participants, as well as the males and females.

Heart Rate Zones

The % of total time spent in each of the five HR zones during HIT and LIT in EVEN and BLOCK for both the males and females is displayed in **Figure 2**. Overall there were no significant differences between interventions in the proportion of total training time spent in each of the HR zones (∼16, 37, 27, 10, and 10% of total time in zones 1–5, respectively, for both interventions). Furthermore, the total sHRZ scores did not differ between EVEN and BLOCK (3,739 ± 440 and 3,684 ± 449, respectively; $P = 0.329$). However, the females demonstrated a significantly higher total sHRZ score during EVEN compared with the males (4,012 ± 392 and 3,466 ± 298, respectively; $P = 0.003$) and a non-significant tendency for the same difference during BLOCK (3,869 ± 520 and 3,498 ± 281, respectively; $P = 0.067$).

Perceived Exertion and Recovery

The median [range] sRPE and pREC scores during each of the separate training weeks for EVEN and BLOCK are displayed in **Table 7**. The total sRPE training loads did not significantly differ between EVEN and BLOCK (7,751 [5,758–9,462] and 8,127

TABLE 4 | Mean ± SD average heart rate (HR_{av}), maximal heart rate (HR_{max}), % of the total training time spent in zones 1–5 (Z1–Z5) and summated heart rate zone (sHRZ) scores and median [range] session rating of perceived exertion (sRPE) scores during low-intensity training (LIT) and high-intensity interval training (HIT).

			All participants	Males	Females
HR_{av} (beats·min^{-1})		LIT	133 ± 9	130 ± 7	136 ± 10
		HIT	153 ± 8**	152 ± 7**	155 ± 9**
HR_{max} (beats·min^{-1})		LIT	159 ± 8	156 ± 3	161 ± 10
		HIT	191 ± 6**	191 ± 6**	192 ± 7**
% of total training time spent in each zone	Z1	LIT	21 ± 15	25 ± 15	16 ± 15
		HIT	11 ± 5**	11 ± 6*	10 ± 5
	Z2	LIT	48 ± 13	56 ± 13	40 ± 7††
		HIT	26 ± 8**	30 ± 6**	21 ± 8†
	Z3	LIT	29 ± 18	18 ± 10	40 ± 18††
		HIT	25 ± 7	22 ± 8	27 ± 6*
	Z4	LIT	2 ± 3	1 ± 1	4 ± 3††
		HIT	19 ± 4**	19 ± 4**	19 ± 5**
	Z5	LIT	0 ± 0	0 ± 0	0 ± 0
		HIT	20 ± 8**	17 ± 6**	23 ± 8**
Total sHRZ score		LIT	3,196 ± 509	2,896 ± 280	3,496 ± 517††
		HIT	4,227 ± 377**	4,069 ± 303**	4,385 ± 390**
Total sRPE score		LIT	5,440 [3,735–6,983]	4,230 [3,735–6,489]	6,186 [3,989–6,983]†
		HIT	10,463 [9,225–11,592]**	10,200 [9,225–11,550]*	10,725 [9,488–11,592]*

*Significantly different from LIT: *$P < 0.05$, **$P < 0.001$.*
Significantly different from the males: †$P < 0.05$, ††$P < 0.01$.

TABLE 5 | Mean ± SD weekly durations (min) for low-intensity training (LIT) during three weeks of evenly-distributed (EVEN) and block (BLOCK) training.

	Week 1	Week 2	Week 3
EVEN	231 ± 29	272 ± 5	239 ± 11
BLOCK	319 ± 9*	0 ± 0*	435 ± 26*

*Significantly different from EVEN: *$P < 0.001$.*

TABLE 6 | Mean ± SD average distance covered (m) during the 4-min high-intensity intervals during three weeks of evenly-distributed (EVEN) and block (BLOCK) training.

	All participants	Males	Females
EVEN	740 ± 71	795 ± 38	675 ± 35*
BLOCK	736 ± 75	792 ± 46	671 ± 43*

*Significantly different from the males: *$P < 0.001$.*

[6,338–10,085], respectively; $P = 0.286$). However, the females demonstrated a significantly higher total sRPE training load for EVEN compared with the males (8,076 [6,140–9,462] and 7,530 [5,758–8,155], respectively; $P = 0.031$) and a non-significant tendency for the same difference during BLOCK (8,423 [7,337–8,948] and 7,740 [6,338–10,085], respectively; $P = 0.190$). The pREC prior to each of the HIT sessions was significantly improved for EVEN compared with BLOCK for all participants (6 [3–10] vs. 4 [1–8], respectively; $P < 0.001$), as well as for the males (6 [3–10] vs. 4 [1–8], respectively; $P < 0.001$) and the females (6 [3–8] vs. 4 [1–8], respectively; $P < 0.001$).

Recovery-Stress State

The overall recovery-stress state (as measured by the RESTQ-Sport) did not significantly differ between EVEN and BLOCK ($P = 0.510$), but was significantly lower (indicating a less recovered/more stressed state) after week two for BLOCK compared with EVEN (14 [1–28] vs. 18 [5–35], respectively; $P = 0.033$). In addition, the females had a significantly lower recovery-stress state compared with the males during BLOCK after week two (11 [1–20] vs. 21 [13–28], $P < 0.001$) and three (15 [0–23] vs. 22 [11–30], $P = 0.014$).

DISCUSSION

The present investigation has shown that a 3-week polarized training intervention incorporating a block distribution of HIT is well-tolerated by a group of male and female junior cross-country skiers. In contrast to the hypothesis, distance covered during HIT was not lower during BLOCK compared with EVEN. In addition, despite weekly differences, overall total sHRZ scores, time spent in each of the HR zones, perceived exertion scores and training loads, perceived recovery and the overall recovery-stress state were not different following BLOCK compared with EVEN. In terms of pre- to post-training, no differences were observed between the changes in any of the performance or physiological measures following the two interventions (see **Table 3**). However,

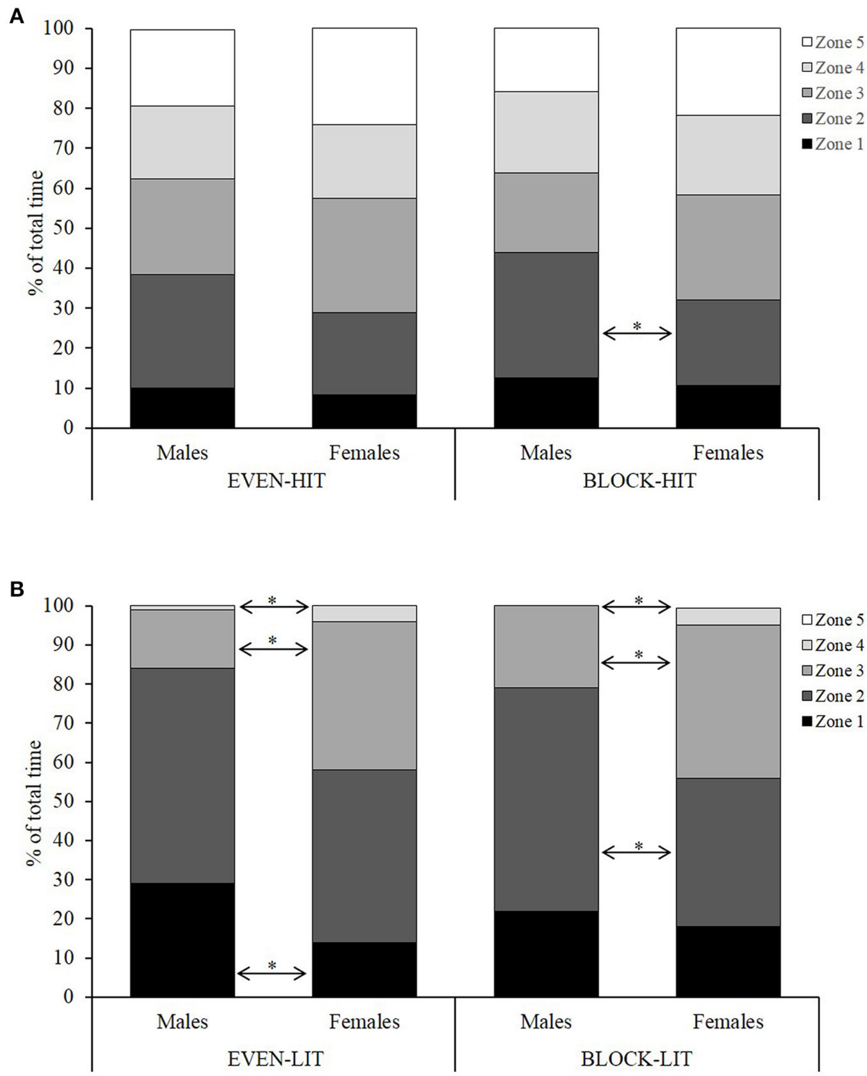

FIGURE 2 | Percentage of the total time spent by the male and female skiers in the five different heart rate zones during the HIT **(A)** and LIT **(B)** sessions for the evenly-distributed (EVEN) and block (BLOCK) training interventions. Significantly different between the males and females: **P* < 0.05.

there were significant time effects for 600-m TT performance and a number of hormonal and muscle biopsy markers, irrespective of intervention. Based on these findings the current study does not support block-distributed HIT as a superior method to evenly-distributed HIT in terms of enhancing physiological or performance adaptions.

Block training is based on the theory that a period of highly concentrated, specialized loading will generate an increase in the training stimulus such that, following a period of recovery, work capacity and performance will increase due to a super-compensation (Issurin, 2008, 2010). At the same time, aerobic-based HIT has been shown to maximize the time spent exercising close to $\dot{V}O_2max$, which is considered the most effective stimulus for developing the oxygen transport and utilization systems (Billat, 2001; Midgley et al., 2006). A number of studies have combined the concepts of block training and HIT, showing positive improvements in $\dot{V}O_2max$, MPO, sub-maximal power output and TT performance among trained athletes following 13–15 HIT sessions completed within 10–14 days (Stølen et al., 2005; Breil et al., 2010; Wahl et al., 2013). While these studies highlight the potential benefits of blocking HIT, they did not compare different types of training organization. Therefore, the observed effects may simply be due to the training stimulus, *per se*, rather than the specific distribution of HIT sessions. More recently, Rønnestad and colleagues have completed a series of studies comparing block- with more evenly-distributed HIT interventions (Rønnestad et al., 2014a,b, 2016). Greater improvements in $\dot{V}O_2max$ were reported for trained cyclists following block- (5 HIT sessions in week 1, 1 HIT session in weeks 2–4) compared with evenly- (2 HIT sessions per week) distributed HIT (Rønnestad et al., 2014a,b). Among competitive cross-country skiers and biathletes, by contrast, improvements

TABLE 7 | Median [range] session rating of perceived exertion (sRPE) and perceived recovery (pREC) scores during the individual evenly-distributed (EVEN) and block (BLOCK) training weeks.

		sRPE			pREC		
		All	**Males**	**Females**	**All**	**Males**	**Females**
EVEN	Week 1	7 [1–10]**	7 [1–9]**	7 [2–10]**	6 [3–9]	6 [4–9]	6 [3–8]
	Week 2	6 [1–9]**	4 [1–9]**	7 [2–9]**	6 [3–10]**	7 [3–10]**	6 [3–8]**
	Week 3	6 [2–10]**	5 [2–10]**	6 [3–10]**	5 [3–8]**†	6 [3–8]†	5 [3–8]**†
	All weeks	6 [1–10]	5 [1–10]	6 [2–10]	6 [3–10]	6 [3–10]	6 [3–8]
BLOCK	Week 1	3 [2–6]††	3 [2–5]††	3 [2–6]††	6 [3–9]††	7 [5–9]††	6 [3–9]††
	Week 2	8 [2–10]	8 [2–10]	8 [4–10]	4 [1–8]	4 [1–8]	4 [1–8]
	Week 3	4 [2–7]††	3 [2–6]††	4 [2–7]††	7 [3–9]††	7 [3–9]††	7 [4–8]††
	All weeks	6 [2–10]	5 [2–10]	7 [2–10]	5 [1–9]	6 [1–9]	5 [1–9]

sRPE, assessed using a modified CR-10 scale with 0 and 10 corresponding to rest and maximal, respectively; pREC, assessed on a scale with 0 and 10 corresponding to very poorly recovered/extremely tired and very well recovered/highly energetic, respectively.
Significantly different from the corresponding BLOCK week: $^{**}P < 0.001$.
Significantly different from week 2: $^{\dagger}P < 0.01$, $^{\dagger\dagger}P < 0.001$.

in $\dot{V}O_2max$ were not greater following block- versus evenly-distributed HIT, but the block training group improved MPO and sub-maximal power output to a greater extent than the even training group (Rønnestad et al., 2016). The current study aimed to investigate the potential mechanisms for the superior effects of block- compared with evenly-distributed HIT by systematically monitoring the daily responses to training (through HR, sRPE, recovery and performance measures), as well as by examining the peripheral adaptations in the muscle through pre- and post-intervention muscle biopsies.

Despite a more intense HIT stimulus applied in the current study compared with Rønnestad et al. (2014a,b); Rønnestad et al. (2016), no significant differences were observed between BLOCK and EVEN for any of the variables measured pre- to post-training (i.e., skiing economy, $\dot{V}O2max$, TT performance, resting salivary markers or muscle biopsy markers). This could be due to a number of reasons relating to the study design. Firstly, the current study was conducted at the end of the cross-country season, whereas all other published block training studies have been completed during pre-season (Breil et al., 2010; Wahl et al., 2013; Rønnestad et al., 2014a,b, 2016). Since Losnegard et al. (2013) have shown that cross-country skiers perform more HIT and less LIT toward the end of the competitive season, it is possible that the timing and resulting training status of the athletes in the present study affected the efficacy of the BLOCK intervention. Another factor could be the lack of any HIT sessions in the final training week during BLOCK. Anecdotally, athletes in the current study reported feelings of lethargy as a result of only having performed LIT in the week prior to laboratory testing. This was not the case following EVEN, whereby three HIT sessions had been performed in the week prior to testing. Bosquet et al. (2007) refer to maintenance of training intensity during an optimal taper and in support of this, Rønnestad et al. (2014a,b, 2016) prescribed at least 1 HIT session per week during recovery following their block intervention. Therefore, the maintenance of some HIT sessions in the weeks following the overload period may be critical in detecting beneficial effects of block training.

As well as investigating a range of pre- to post-training markers to assess the efficacy of BLOCK compared with EVEN, a large focus of the current study was directed toward examining the responses during training, in order to explain any potential differences between the two interventions. It was expected that less total distance would be covered during the HIT sessions in BLOCK compared with EVEN, due to the reduced recovery between sessions and subsequent accumulation of fatigue. For instance, power output produced by endurance-trained athletes has been observed to be lower during a second session of HIT performed on the same day compared to on a separate day (Yeo et al., 2008). Unexpectedly, however, the average distance covered during the 5 × 4-min intervals was similar between the two interventions in the present study (∼740 m per interval). In contrast to Yeo et al. (2008), who allowed only 2 h of rest and water consumption between sessions, participants in the current study rested for 4–5 h and ate a meal between any two HIT sessions on the same day. Therefore, longer recovery and energy replacement may help to maintain performance when completing two HIT sessions on the same day. Alternatively, the whole-body nature of cross-country skiing exercise may lead to reduced local fatigue and allow training intensities to be maintained during a second training session within a day. The relatively long recovery duration of 6 min between each interval, which resulted from the logistical requirement for athletes to jog back down the hill after each interval, may also have enabled the maintenance of work done over the five repetitions. In fact, as little as 2 min of recovery between 4-min HIT bouts has been shown to be sufficient in maintaining performance in a set of repeated intervals, although a higher average oxygen consumption was possible during intervals with a 2- vs. 4-min recovery period (Seiler and Hetlelid, 2005).

Similar to distance covered, it was also expected that the athletes in the current study would attain lower HRs during

BLOCK compared with EVEN, due to the more concentrated training load and reduced recovery between HIT sessions. This response has previously been demonstrated for competitive cyclists during maximal exercise following a period of intensified training predominantly consisting of HIT (Jeukendrup et al., 1992). However, no differences were identified in total sHRZ scores or the time spent in each of the HR zones during EVEN compared with BLOCK. With no differences observed for the group as a whole, further analyses were conducted to compare differences in the responses between the males and females. Interestingly, the females demonstrated a higher sHRZ score than the males during EVEN, with a non-significant tendency for the same difference during BLOCK. This appears attributable to the fact that the females spent more time in zones 3 and 4 during the LIT sessions, while the males spent more time in zones 1 or 2. While only speculative, it is possible that some of the females worked relatively harder during the LIT sessions in order to "keep up" with other members of the training group. While the athletes typically trained with others of a similar standard, a group session may have put pressure on the weaker members (often females) to work at a higher relative intensity than the stronger members (often males). Furthermore, any common undulating training routes, where specific techniques (and therefore velocities, to a certain extent) are employed on given inclines, would also likely lead to higher relative intensities among the females due to lower maximal aerobic capacities. In addition to differences during the LIT sessions, the males also spent significantly more time in zone 2 during the BLOCK HIT sessions, with the females tending to spend more time in the higher HR zones. This indicates a more rapid HR recovery among the males between intervals. Overall these findings highlight the need for coaches to carefully monitor the internal loads (i.e., HR responses) of individuals within a training group, especially in mixed-sex groups, to ensure that specified training targets are achieved.

Subjective measures have been reported to be more sensitive and consistent than objective measures when monitoring changes in athlete well-being in response to training (Saw et al., 2016), hence the use of sRPE, pREC, and RESTQ-Sport in the current study. An analysis of the separate weeks highlighted clear distinctions in the differing demands during BLOCK and EVEN, with sRPE scores significantly higher and pREC scores significantly lower during week two of BLOCK compared with weeks one and three, as well as compared with week two of EVEN. In addition, pREC was improved prior to the HIT sessions during EVEN compared to BLOCK. This indicates an improved readiness to train when HIT sessions are spread out over 3 weeks rather than being condensed into 1 week. The extreme training load prescribed in week two of BLOCK was the basis for hypothesizing that perceived exertion would have been higher and perceived recovery would have been lower after BLOCK compared with EVEN. However, results showed no differences in sRPE scores, sRPE training loads or average pREC scores after the two, 3-week interventions. Interestingly, and consistent with the sHRZ data, the females demonstrated a significantly higher sRPE training load during EVEN compared with the males and a tendency for the same difference during BLOCK. This may be for a similar reason to that previously proposed; that is, higher relative intensities and more time spent in higher HR zones may have resulted in a higher perception of effort among the females compared with the males.

Previous studies investigating periods of intensified training among endurance athletes have shown short-term reductions in recovery and well-being, as well as increases in mood disturbance and stress levels (Jeukendrup et al., 1992; Halson et al., 2002; Jürimäe et al., 2004; Coutts et al., 2007). Since an excess of stress can result in long-term performance decline that is manifested as overtraining, or non-functional OR (Meeusen et al., 2013), there was a potential risk for the young athletes in the current study performing so many HIT sessions within 1 week. Therefore, the RESTQ-Sport, which has been identified as a useful tool for monitoring perceived stress and recovery among athletes (Saw et al., 2016), was administered weekly (in contrast to the session-based pREC scale). Despite a significant difference during week two, the overall recovery-stress state was not different following BLOCK compared with EVEN. A rapid restoration of the recovery-stress state is consistent with previous findings that have shown global mood state to recover to baseline after 4–6 days of easy training (Halson et al., 2002). Therefore, it seems that non-functional OR may be avoided by limiting the duration of the intense training period and allowing sufficient recovery afterwards. An interesting and unexpected finding in the current study was that the females demonstrated lower recovery-stress states compared with the males, with the largest differences observed after week two of BLOCK. Thus, this study provides novel data to suggest that female athletes are more vulnerable than males to the stressors associated with block-distributed HIT within a polarized microcycle, perhaps due to higher internal workloads during training sessions.

The current study is the first to have comprehensively compared the responses during, and effects of, two polarized training models differing only in the distribution of training sessions. Due to the high adherence rates (90–100% of sessions completed by all individuals during HIT and LIT), the results may be considered a true representation of the prescribed interventions. Findings have shown distinct demands on the athletes during the three separate weeks of EVEN and BLOCK, demonstrated by the significant weekly differences in time spent performing LIT and HIT, perceived exertion and recovery scores and recovery-stress states. Despite this, the overall responses during the two interventions were typically similar in terms of performance and subjective measures (i.e., distance covered during HIT, session ratings of perceived exertion, perceived recovery and recovery-stress states). Moreover, changes pre- to post-training did not differ between EVEN and BLOCK. Some limitations of the present study may be related to the experimental design, specifically the lack of any HIT sessions following the intensified training week, the relatively short duration between the intensified training week and follow-up laboratory tests, the short time period (3 weeks) over which the interventions were prescribed and/or the relatively long recovery duration (6 min) between the 4-min HIT intervals. Nevertheless, a novel aspect of the study is the comparison between males and females, which revealed some real practical issues for coaches whereby the females typically demonstrated higher HR responses and sRPE scores, as well as higher stress scores and lower recovery-stress states, compared to the males. In light of these specific differences, future research may be directed toward investigating how higher internal training loads, perceived exertion and subjective recovery-stress states in females influence long-term training adaptations and potential OR or overtraining. In conclusion, the current study has shown that well-trained junior cross-country skiers are able to complete 9 HIT sessions within 1 week without compromising total work done or experiencing greater stress or reduced recovery in comparison to completing 3 HIT sessions per week over 3 weeks. However, a short training intervention using block-distributed HIT is not supported as being superior to evenly-distributed HIT when applied to well-trained, junior cross-country skiers.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Regional Ethical Review Board (Umeå Sweden) with written informed consent from all subjects (and informed parental consent for those aged under 18 years). All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Regional Ethical Review Board, Umeå University, Umeå Sweden.

AUTHOR CONTRIBUTIONS

KM, EJ, and HH made substantial contributions to the conception and design of the work while KM, EJ, ZK, KS, EB, OH, and HH all made substantial contributions to the acquisition, analysis and interpretation of data for the work. All authors (KM, EJ, ZK, KS, EB, OH, and HH) were involved in the drafting and critical revision of the work, as well as the final approval of the version to be published, and agree to be accountable for all aspects of the work.

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Is Marathon Training Harder than the Ironman Training? An ECO-method Comparison

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Purpose: To compare the absolute and relative training load of the Marathon (42k) and the Ironman (IM) training in recreational trained athletes.

Methods: Fifteen Marathoners and Fifteen Triathletes participated in the study. Their performance level was the same relative to the sex's absolute winner at the race. No differences were presented neither in age, nor in body weight, height, BMI, running VO_{2max} max, or endurance training experience ($p > 0.05$). They all trained systematically for their respective event (IM or 42k). Daily training load was recorded in a training log, and the last 16 weeks were compared. Before this, gas exchange and lactate metabolic tests were conducted in order to set individual training zones. The Objective Load Scale (ECOs) training load quantification method was applied. Differences between IM and 42k athletes' outcomes were assessed using Student's test and significance level was set at $p < 0.05$.

Results: As expected, Competition Time was significantly different (IM 11 h 45 min ± 1 h 54 min vs. 42k 3 h 6 min ± 28 min, $p < 0.001$). Similarly, Training Weekly Avg Time (IM 12.9 h ± 2.6 vs. 42k 5.2 ± 0.9), and Average Weekly ECOs (IM 834 ± 171 vs. 42k 526 ± 118) were significantly higher in IM ($p < 0.001$). However, the Ratio between Training Load and Training Time was superior for 42k runners when comparing ECOs (IM 65.8 ± 11.8 vs. 42k 99.3 ± 6.8) ($p < 0.001$). Finally, all ratios between training time or load vs. Competition Time were superior for 42k ($p < 0.001$) (Training Time/Race Time: IM 1.1 ± 0.3 vs. 42k 1.7 ± 0.5), (ECOs Training Load/Race Time: IM 1.2 ± 0.3 vs. 42k 2.9 ± 1.0).

Conclusions: In spite of IM athletes' superior training time and total or weekly training load, when comparing the ratios between training load and training time, and training time or training load vs. competition time, the preparation of a 42k showed to be harder.

Keywords: training intensity distribution, polarized training, training load quantification, endurance training, marathon, ironman

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INTRODUCTION

The interest of recreational athletes in long distance events has been constantly growing in the last 30 years. As a sample of this, the world's marathon majors circuit reached about 200,000 runners in 2015 (WMM, 2016), while in triathlon, the Ironman® corporation events reached about 70,000 (WTC, 2016). The Ironman (IM) and Marathon (42k) distances are the classical longest endurance events in their respective sports. These events require large amounts of training (O'Brien et al., 1993; Laursen and Rhodes, 2001), so monitoring the training load becomes a must in order to prevent over reaching or overtraining (Halson, 2014).

"Training Load" (or training *stimulus*) implies the combination of the mode of exercise and the dose of the volume, intensity, and density or frequency (Wenger and Bell, 1986; Bompa and Haff, 2009). Quantifying the training load becomes of key importance, since it helps to consider the real demands of a given sport discipline (Bompa and Haff, 2009). There are many studies describing the physiological demands of a long distance event competition (Föhrenbach et al., 1987; O'Brien et al., 1993; Laursen and Rhodes, 2001), but few studies focused on the training load leading to a given performance (Esteve-Lanao et al., 2007; Guellich and Seiler, 2010; Seiler, 2010; Neal et al., 2013; Muñoz et al., 2014a,b; Stöggl and Sperlich, 2014). Bearing in mind that it is difficult to establish the precise amount of training load that an athlete needs (Seiler and Tønnessen, 2009), several studies have been focused on training intensity distribution between professional and recreational athletes including different disciplines (Robinson et al., 1991; Lucía et al., 2000, 2003; Billat et al., 2001; Esteve-Lanao et al., 2005; Seiler and Kjerland, 2006; Guellich et al., 2009). Different methods have been proposed to quantify training load (Borresen and Lambert, 2009). One of the few methods (if any) that allow the comparisons of the training load between different modes of exercise (i.e., running vs. swimming or cycling) is the Objective Load Scale (ECO in Spanish) method (Cejuela and Esteve-Lanao, 2011).

Since there are no data comparing athletes of different sports who perform at similar level for IM and 42k (i.e., trained recreational athletes), and starting from the simplistic athletes' question of "how hard it is" to be ready for these challenges, the goals of our study were: (1) To observe the differences between IM and 42k training load and (2) To observe the correlation between the competition time and the training intensity distribution at each group of endurance athletes.

METHODS

Participants

Thirty recreational level athletes (15 long distance triathletes and 15 marathon runners) participated in the study. Both groups had 13 male and 2 females. They all volunteered and gave written informed consent to participate in the study, which had been approved by the Universidad Europea Ethical Advisory Committee. They all lived and trained in Spain, with the same coach (J. E-L). Their main goal for the season was to perform their best at an Ironman distance triathlon (3.8k swim, 180k cycle, and 42.1k run) or a Marathon (42.195k) race. Training and competitive experience in endurance sports was similar between subjects (∼7 years). Subjects' descriptive characteristics are shown in **Table 1**.

Main Characteristics of Training and Periodization

Both 42k (runners) and IM (triathletes) groups completed a 16 weeks macrocycle (**Figure 1**). Global load was designed to alternate every 3 weeks of hard training load with an easy, lower load week (4, 4 weeks mesocycles). They followed an inverse periodization model, so that the peak training volumes were prescribed between weeks #10 and #11.

Hydration and nutritional guidelines were followed during these sessions, based on personal interviews with a sport nutrition specialist, including the calculation of the sweating rate. Time of day was set early in the morning for running or cycling sessions in order to minimize potential heart rate drift effects (Poole et al., 1994). Swimming sessions for triathletes were conducted twice to three times a week in the evening. Racing conditions were similar for both types of events (including temperature, humidity, altitude, and profile) and they were held in Spain during the spring season.

No differences were applied to the programs in strength training. This training was based on maximal strength development with moderate loads during the initial 11 weeks. It consisted in progressive workouts starting with resistance training machines. Loads progressed from 2 to 4 sets per muscle group, 25–8 reps, 40–75% of estimated 1RM through submaximal testing calculations. Those exercises were replaced at week 4 by multi-joint exercises. Loads were gradually increased in a similar fashion as mentioned before. Resistance training was gradually combined with specific strength methods in every sport (paddles for swimming, hills, or harder gears for cycling, light weighted belts for running) between weeks 5 and 13. By the end of the macrocycle, some basic maintenance resistance training on machines was conducted with moderate loads (60–70% of estimated 1RM), low number, explosive-velocity

TABLE 1 | Samplee characteristics.

	Ironman ($n = 15$)	Marathon ($n = 15$)	t_{28}	p
Age (years)	39.1 (7.5)	38.2 (7.6)	0.34	0.737
Weight (kg)	70.9 (8.3)	69.7 (8.1)	0.42	0.675
Height (cm)	174.5 (7.3)	175.2 (5)	−0.32	0.751
BMI (kg/m^2)	23.3 (2.4)	22.7 (2.3)	0.71	0.482
VO_{2max} (ml/min/kg)	56.1 (6.1)	57.5 (6.8)	−0.61	0.550
Training experience (year)	7.1 (2.1)	7.3 (2.3)	−0.41	0.672
Relative performance (%)	140.4 (24.5)	143.7 (22.2)	−0.38	0.705
Competition time (min)	704.6 (113.6)	186.5 (27.9)	17.15	<0.001
Same sex's absolute winner time (min)	503.7 (33.7)	130.1 (4.9)	42.49	<0.001

Relative performance was calculated dividing competition time by absolute winner's time, considering the sex of each participant.

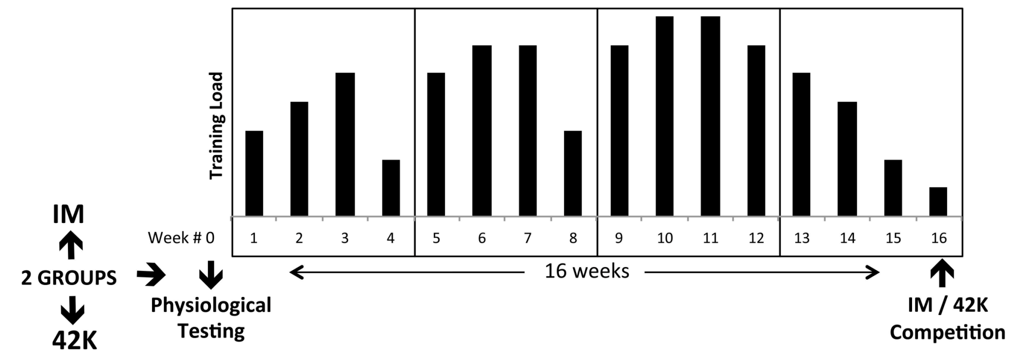

FIGURE 1 | Experimental design. Planned training load is described with arbitrary units, with the purpose of showing general trend of hard/easy weeks.

reps. Two sessions a week were programed (for most of the weeks with exception of the taper phase and the 4th weeks during each mesocycle). About 1.75 (0.20) sessions/week were reported. However, the training load for strength training was not quantified for this study.

No speed training or any other workouts beyond VO_{2max} zone were prescribed.

Baseline Physiological Testing and Training Zones Settings

Before starting the training program, all athletes participated in short-distance events macrocycles (10k or Half-Marathon for runners, Sprint or Olympic distance for triathletes), followed by a 3–4 weeks transition period. One week before starting the 16-week macrocycle, during that transition period, graded exercise tests were used to determine training zones.

Swimming tests were performed as a graded multi-stage test consisting of 7 repetitions of 200 m with 2 min rests (Pyne and Sweetenham, 2003). Heart rate (HR, beats·min^{-1}) and blood lactate (bLA, mMol·L^{-1}) samples from the earlobe were analyzed with a portable lactate analyzer (Lactate Pro, Arkray Inc, Amstelveen, NED). Triathletes were familiar with the Rating of Perceived Exertion (RPE) (Borg, 1998), so RPE 0–10 scale was applied immediately after collecting HR data and LA samples.

Threshold criteria were defined as follows: blood lactate 0.5 mMol·L^{-1} increase toward previous stage for Aerobic Threshold (AeT), >1.0 mMol·L^{-1} increase for Anaerobic Threshold (AnT), and 8–9 mMol·L^{-1} for Maximal Aerobic Velocity (MAV) (Beneke, 2003; Billat et al., 2003).

Cycling and running tests were conducted with a gas exchange analyzer (VO2000, Medical Graphics, St, Paul, MA, USA). A ramp-protocol test was conducted for cycling on an ergometer (Sensormedics, Yorba Linda, CA, USA) starting at 50 W and increasing 5 W every 12 s (Lucía et al., 2000). Two independent observers identified AeT and AnT. The following variables were measured: oxygen uptake (VO_2), pulmonary ventilation (VE), ventilatory equivalents for oxygen ($VE{\cdot}VO_2^{-1}$), and carbon dioxide ($VE{\cdot}CO_2^{-1}$), and end-tidal partial pressure of oxygen ($P_{ET}O_2$) and carbon dioxide ($P_{ET}CO_2$).

Running tests were conducted on a treadmill (Technogym Run Race 1400 HC, Gambettola, Italy), with a starting velocity of 8 km·h^{-1}, increased by 0.3 km·h^{-1} every 30 s until volitional exhaustion (Esteve-Lanao et al., 2007; Muñoz et al., 2014b).

For both cycling and running tests, standardized criteria were used for VO_{2max} achievement, AnT and AeT determination and HR recordings, following previously described procedures (Muñoz et al., 2014a,b).

Training Intensity Distribution and Training Load Quantification

Based on the classical 3-phase model of Skinner and McLellan (1980), and for practical purposes in terms of training intensity distribution analysis, three main zones were differentiated: <AeT (at or below AeT), BAeT-AnT (between thresholds, precisely beyond AeT and below AnT) and >AnT (at or beyond AnT). Of note, all data were included, both warm-ups and cool-downs, thus not following the so-called "Session Goal Aproach" applied in other studies (Seiler, 2010).

For daily training workouts, these three zones were subdivided into narrower ranges (dividing each zone for being more precise in some workouts, and adding a Maximal Aerobic Power zone for some swimming workouts), up to a total of 6 zones from <AeT to Maximal Aerobic Power plus 2 "anaerobic" zones. Microsoft® Excel® Training logs were designed to calculate training load based on the methodology of ECOs (Cejuela and Esteve-Lanao, 2011) which was specially developed for training quantification in triathlons, so that it is suitable for comparisons to any single event sport.

This methodology seems the most appropriate when comparing different endurance activities, as different exercise modes show different degrees of muscle damage, energy cost, effort densities, and differences at the ability of maintaining technique (Cejuela and Esteve-Lanao, 2011).

The Percentages of time spent at <AeT, BAeT-AnT, and >AnT were calculated by the training log dividing the total time spent during a workout at a given zone by the total exercising time during the workout and multiplied by 100. The training logs were prepared in order to record every session and to differentiate running or triathlon (swim/bike/run) sessions and calculations.

Briefly, the ECOs were calculated by multiplying the total duration of a training session (in minutes) with a scoring value between 1 and 50, depending on the heart rate-based training zone (1–8) and by a factor of 1.0, 0.75, or 0.5 for running, swimming or biking, respectively. Daily and weekly training loads (ECOs) of each subject were quantified. For example, a 60 min running session at Zone 1 is scored like this: $60 \times 1 \times 1$, since Running has a factor of "1," and Zone 1 has a factor of "1." However, a 2-h cycling session at zone 1 also scores "60," since Cycling has a factor of "0.5" ($120 \times 1 \times 0.5$). Another example (in the case of an interval training workout), would be a 12×100 m swimming workout at zone 4 plus other 20 min of zone 1 swimming adding the warm up and the cool down. If the swimmer would we performing at 1 min 40 s per rep, this would be a total of 20 min at zone 4. Thus, if the swimmer would we performing 20 (min) × Zone 1 is 20, and multiplied by 0.75 scores 15. When adding the other 20 min interval net time at Zone 4 per 0.75 is 60, so the total session scores 75 ECOs.

Both runners and triathletes were filling manually personal training logs with the information recorded in their HR monitors, considering net training time from the whole session, in terms of the amount of time spent per training zone at each sport (Cejuela and Esteve-Lanao, 2011).

Speed, Power or Pace values corresponding to the training zones were increased during the program according to RPE/HR initial training zones, as previously described (Muñoz et al., 2014a) and based on the reported validity of these lab references during a subsequent period of several months (Lucía et al., 2000). RPE was considered appropriate for technical swimming exercises and also when HR recording showed any anomalous display or abnormality.

Training Loads were designed to meet a mean (SD) of ∼15,313(2,087) ECOs for the IM and 8,333(699) for 42k. The reason for this SD was that different programs were designed according to performance level differences, plus other considerations such as time availability or training experience. General training intensity distribution was scheduled week by week, with a global mean of 84/7/9%, respectively, in Zones 1/2/3 (IM 78/19/3, 42k 86/2/12).

Inclusion criteria were the following: (1) to complete 85% of total training sessions, (2) to record 95% of total training sessions, and (3) to complete and perform continuously, without any relevant health, tactical, or technical problems, the full distance in competition performing as best as possible.

Data Analysis

Training accomplishment was calculated dividing the training logs reported data by the prescribed training loads. Relative performance (%) was calculated dividing competition time by absolute winner's time, considering the sex of each participant, and multiplying the result by 100. Data were summarized as mean (standard deviation). Differences between IM and 42k athletes' outcomes were assessed using Student's t-test. Association between performance and training time and loads were assessed using Pearson's product-moment correlation coefficients. This statistical analysis was performed using SPSS version 22 (SPSS Inc., Chicago, Illinois, USA). The significance level was set at 0.05.

RESULTS

As shown in **Table 1**, IM and 42k athletes did not show any significant difference in age, weight, height, body mass index, nor VO_{2max}. Additionally, their relative performance, compared to their sex's absolute winner, was also equivalent (40.4 and 43.7% over the winner's time, respectively). Mean performance time was 11 h 45 min for IM and 3 h 06 min for 42k.

Training logs were reported weekly and were filled by all the athletes. No relevant injuries, tactical or technical problems appeared along the training program or competitions. Based on total ECOs, an average of 98.7(20.2)% accomplishment was found.

As shown in **Table 2** (or equivalently in **Figure 2**), IM athletes' loads were significantly higher during the greater part of training cycle. IM athletes invested significantly more time and ended up at higher loads, with higher weekly averages. Training peaks in time and loads were also significantly higher for IM athletes (**Table 3**).

Peak Training Load was located about the same period from competition in both groups (between 6th and 8th before competition). During the last 4 weeks, the loads were reduced in both groups, but more markedly in IM, so that no differences were found during that last mesocycle.

Although no significant differences were found in relative time and load in zone <AeT, IM athletes showed significantly higher relative times and loads in zone BAeT-AnT, while 42k runners' relative time and load in zone >AnT were significantly higher (**Table 3**).

Ratios of training load by training time in 42k runners showed significantly higher relative training load [$t_{(28)} = -9.50$,

TABLE 2 | Training Load per week (ECOs, weeks 1–16).

Week (#)	Ironman (n = 15)	Marathon (n = 15)	t_{28}	p
1	677.2 (169.4)	348.6 (162.5)	5.42	<0.001
2	834.8 (163.6)	540 (146.7)	5.20	<0.001
3	961.1 (276)	452.4 (190.7)	5.87	<0.001
4	826.6 (260.3)	575.5 (143)	3.27	0.003
5	977.1 (296)	535.9 (143)	5.20	<0.001
6	842.7 (251)	608.7 (143)	3.14	0.005
7	946.7 (404.9)	554.7 (136.8)	3.55	0.002
8	863.5 (193.5)	529.6 (162.2)	5.12	<0.001
9	970.7 (310.2)	561.2 (185)	4.39	<0.001
10	1044.3 (381.3)	665.4 (218.5)	3.34	0.002
11	1064.9 (400.8)	647.7 (227.5)	3.51	0.002
12	897.3 (248.9)	555.3 (225.2)	3.95	<0.001
13	710.7 (274.5)	621.7 (214.2)	0.99	0.331
14	807.8 (347.1)	561.3 (229.6)	2.30	0.031
15	592.1 (267.6)	453.0 (239.5)	1.50	0.145
16	210.5 (160.8)	206.0 (72.8)	0.10	0.923

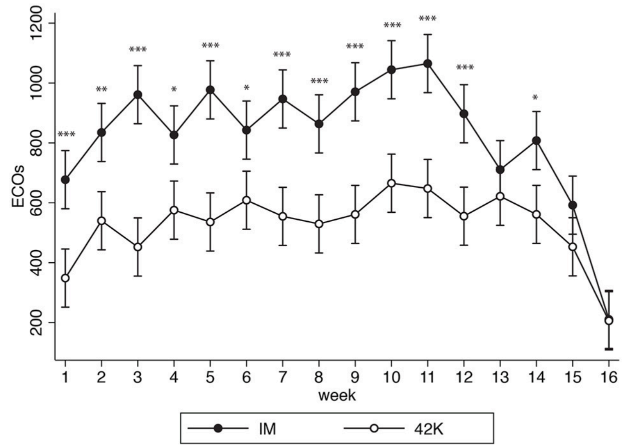

FIGURE 2 | Comparison of IM (black) and 42k (white) weekly training loads (ECOs) during 16 weeks. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

$p < 0.001$]. Additionally, ratios of training time [$t_{(28)} = -3.99$, $p < 0.001$] and load relative to competition time [$t_{(28)} = -6.69$, $p < 0.001$] also favored 42k runners.

When observing correlations with performance time, both groups showed significant, inversely related correlations between total training time and performance (the more training time, the better performance). However, only the 42k group showed large and significant correlation between total training load and performance.

Relative time and loads in zone <AeT showed a negative association to performance only for IM, but not for 42k (where only time in Zone <AeT was significantly related). Conversely, absolute and relative time in zone >AnT, and relative load in zone >AnT, showed a negative association to relative performance only for 42k, but not for IM. Relative time and loads in zone BAeT-AnT showed a significant association with poor performance for both groups (so more training time or load BAeT-AnT, the worst performance). Total training time in Zone BAeT-AnT did not show significant associations (see **Table 4**).

DISCUSSION

Both groups presented a significant association between more <AeT training and better performance. However, the opposite association was found with BAeT-AnT, so that the more you train "moderate," the worse in IM or 42k. This agrees with previous studies conducted with age-group IM triathletes (Muñoz et al., 2014a), recreational 10k runners (Muñoz et al., 2014b), and trained Cross Country runners (Esteve-Lanao et al., 2005, 2007). To our knowledge, this is the first study to identify these associations in recreational trained marathon runners.

Interestingly, >AnT was associated to better performance in 42k but not in IM. According to the existing literature (O'Brien et al., 1993; Laursen and Rhodes, 2001), we suspect that physiological intensity differences between these two events might explain this. In contrast with the opposite pattern shown between performance and "easy" (<AeT) or "moderate" (BAeT-AnT) zones time or load, "intense" >AnT zone seems to be linked to a better 42k performance, but not in IM. Again, the superior intensity which marathoners perform seems to explain why this association might be found. For instance, a 3 h marathoner (like those in our study) will average around 70% of VO_{2max} during the race (O'Brien et al., 1993), which would be BAeT-AnT zone in our runners' assessments. However, only during the swimming it might be reasonable to exert beyond AeT (and maybe at some particular moments on the bike) during an IM distance triathlon (Muñoz et al., 2014a). Thus, this opens new insights for the general assumption of the benefits of "Polarized Training Distribution," so that it might not be "always better" for all disciplines. In fact, previous studies reported polarized distribution in top elite marathoners (Billat et al., 2001), but not in recreational IM distance triathletes (Neal et al., 2011; Muñoz et al., 2014a).

The training intensity distribution found in this study (considering both groups) is in line with other sports (Billat et al., 2001; Lucía et al., 2003; Fiskerstrand and Seiler, 2004; Seiler and Kjerland, 2006; Guellich and Seiler, 2010). One of the more active groups of researchers in this issue is Seiler's (Seiler and Kjerland, 2006; Seiler and Tønnessen, 2009; Seiler, 2010) who pointed out a 75-5-20 or even 80-0-20 distribution as "optimal," which seems to be really difficult to achieve unless discarding the warm-ups and cool-downs. Had we done it, we would have probably reached superior >AnT zone percentage. However, as previously described, since they were recreational athletes (i.e., reduced time and training frequency) the training programs increased the weekly time spent in easy zones by using relatively long warm-ups and cool-downs.

Load dynamics were not exactly as originally designed. Peak load week was approximately the same between groups, although tapering was different. In any case, the tapering technique was progressive, particularly in 42k. As previously discussed in the literature, progressive, non-linear tapering techniques seem to have a more pronounced positive impact on performance than step-taper strategies (Mujika and Padilla, 2003).

As suspected, IM athletes trained more than 42k runners. Particularly, IM group trained about more than twice in time and about 1/3 in training load. Recently, it was reported that national level triathletes trained an average of 1,256 ECOs per week over the same period of time as our study (unpublished data from Saugy et al., 2016). Triathletes in our study averaged 834. Top Class Marathoners (according to our calculations using the ECOs method), were 1,200 ECOs whilst trained marathoners would be around 1,000 weekly (Billat et al., 2001). The marathoners in our study averaged 526 ECOs. These and future data might help general references toward optimal doses in relation to performance level, sports and events, although it is known that training response and performance outputs are multifactorial, including genetics (Smith, 2003).

The original question of this study was about "how hard it is" to train for an IM vs. for a 42k. The approach that has been conducted compares training time and load in relation to competition. For instance, classical swimming volumes are tremendously high compared to the competition distance

TABLE 3 | Load description as total values, weekly averages, percentages of load by zone, peak values, and relative loads to training and competition time.

	Ironman ($n = 15$)	Marathon ($n = 15$)	t_{28}	p
TOTALS				
Total training time (h)	206.7 (40.8)	84.3 (15.5)	10.86	<0.001
Total training load (ECOs)	13347.1 (2732.5)	8416.6 (1887.8)	5.75	<0.001
WEEKLY AVERAGES				
Training weekly avg time (h)	12.9 (2.6)	5.2 (0.9)	10.90	<0.001
Training weekly avg time (min)	775.5 (153.7)	311.4 (56.2)	10.98	<0.001
Average weekly load (ECOs)	834.1 (170.7)	526 (118.1)	5.75	<0.001
TRAINING BY ZONES				
% of Time in zone <AeT	67.5 (13.6)	74.6 (3.9)	−1.94	0.070
% of Time in zone BAeT-AnT	28.4 (11.8)	15.6 (4.9)	3.87	0.001
% of Time in zone >AnT	4.3 (2.3)	9.7 (3.9)	−4.64	<0.001
% of Load in zone <AeT	45.8 (11.9)	48.3 (5)	−0.74	0.470
% of Load in zone BAeT-AnT	40.8 (9.8)	26.5 (8.1)	4.37	<0.001
% of Load in zone >AnT	13.7 (5.7)	25.1 (10.4)	−3.75	0.001
PEAKS				
Training time peak (h)	20.9 (4.8)	8.8 (1.8)	9.17	<0.001
Peak load (ECOs)	1345.5 (355.1)	838.1 (178.9)	4.94	<0.001
Peak load week (#)	7.9 (1.9)	6.5 (2.7)	1.63	0.115
RATIOS BY TRAINING TIME				
Training load (ECOs)	65.8 (11.8)	99.3 (6.8)	−9.50	<0.001
RATIOS BY COMPETITION TIME				
Training time (h)	1.1 (0.3)	1.7 (0.5)	−3.99	<0.001
Training load (ECOs)	1.2 (0.3)	2.9 (1)	−6.69	<0.001

TABLE 4 | Correlation coefficients (and *p*-value) between performance (min) and training load distribution.

	IM	42k
TOTAL		
Total training time (h)	−0.59 (0.021)	−0.80 (<0.001)
Total training load (ECOs)	−0.04 (0.894)	−0.73 (0.002)
ZONE <AeT		
Training time in zone <AeT	−0.74 (0.002)	−0.82 (<0.001)
% of Time in zone <AeT	−0.70 (0.004)	−0.10 (0.723)
% of Load in zone <AeT	−0.60 (0.019)	0.37 (0.175)
ZONE BAeT-AnT		
Training Time in zone BAeT-AnT	0.47 (0.075)	0.11 (0.700)
% of Time in zone BAeT-AnT	0.71 (0.003)	0.65 (0.009)
% of Load in zone BAeT-AnT	0.54 (0.038)	0.79 (<0.001)
ZONE >AnT		
Training time in zone >AnT	0.33 (0.223)	−0.77 (0.001)
% of Time in zone >AnT	0.44 (0.099)	−0.74 (0.002)
% of Load in zone >AnT	0.33 (0.234)	−0.81 (<0.001)

(Mujika et al., 1995). The findings of our study state that 42k training is harder in relation to the competition demands. Training Load per training hour is significantly higher (99.3 ECOs in 42k vs. 65.8 in IM), which is about 1.5 ECOs in 42k training, vs. 1 ECO per min in IM. Moreover, Average Weekly Training Load per every minute spent in competition is higher for 42k (2.9 vs. 1.2), as well as the training time invested per every minute in competition (1.7 vs. 1.1, 42k vs. IM). This is the first study to compare athletes from similar level. Further studies will have to present new comparisons in terms of performance level, sports and disciplines.

The main limitation in our study was that it was conducted with athletes who were trained by the same coach, so the applicability of the results should be restricted to similar conditions. This was done because it allowed a better control of many aspects of the program (such as baseline loads, mesocycles distributions, program length, peak volume location, taper design, strength, and speed training methodology, and training supervision). General training intensity distribution was scheduled to be ∼84/7/9%, respectively, in Zones 1/2/3. However, it showed a global mean of ∼72/20/8%, respectively, in Zones 1/2/3. IM should be ∼78/19/3% but it was ∼68/28/4%, 42k should be ∼86/2/12%, but it was ∼74/16/10%. This training intensity distribution has been classified as "pyramidal" (Stöggl and Sperlich, 2015). According to Zone 1 and Zone 2 distributions, both showed a standard deviation of ∼11% among all athletes and both groups. Consequently, in spite of sharing the same coach supervision, a high variability between programs' loads, accomplishment and intensity distribution were given.

The ECOs method has been recently used in a dozen of peer-reviewed papers with elite and high level athletes (Debevec et al., 2015; Hauser et al., 2016; Saugy et al., 2016; Villaño et al., 2016). Further studies should focus on training tolerance between different athletes' disciplines but including biomarkers to relate these theoretical training load comparisons and discriminate between hormonal status, muscle damage, oxidative stress levels or others.

CONCLUSIONS

The highest associations between performance and training were found with time and % of time in zone <AeT for IM, whilst in 42k it was related to the zone <AeT time or load, plus the accumulation of any variable related to >AnT.

In spite of IM athletes' superior training time and total or weekly training load, and according to the ratios between training load and training time, and training time or training load vs. competition time, the preparation of a 42k showed to be harder.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Ethics Committee of the Universidad Europea de Madrid, with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the Universidad Europea de Madrid.

AUTHOR CONTRIBUTIONS

JE and RC made the general design. JE trained the athletes. JE, RC, IM, and EL wrote the manuscript. DM and CC participated in the data acquisition conducting the performance tests, supervising the training workouts, supplying on line assistance and preparing the data. EL analyzed the data and wrote a substantial part of the results section. SS reviewed the manuscript and made important contributions to the final edition.

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METHODS
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Intensity- and Duration-Based Options to Regulate Endurance Training

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The regulation of endurance training is usually based on the prescription of exercise intensity. Exercise duration, another important variable of training load, is rarely prescribed by individual measures and mostly set from experience. As the specific exercise duration for any intensity plays a substantial role regarding the different kind of cellular stressors, degree, and kind of fatigue as well as training effects, concepts integrating the prescription of both intensity and duration within one model are needed. An according recent approach was the critical power concept which seems to have a physiological basis; however, the mathematical approach of this concept does not allow applying the three zones/two threshold model of metabolism and its different physiological consequences. Here we show the combination of exercise intensity and duration prescription on an individual basis applying the power/speed to distance/time relationship. The concept is based on both the differentiation of intensities by two lactate or gas exchange variables derived turn points, and on the relationship between power (or velocity) and duration (or distance). The turn points define three zones of intensities with distinct acute metabolic, hormonal, and cardio-respiratory responses for endurance exercise. A maximal duration exists for any single power or velocity such as described in the power-duration relationship. Using percentages of the maximal duration allows regulating fatigue, recovery time, and adaptation for any single endurance training session. Four domains of duration with respect to induced fatigue can be derived from maximal duration obtained by the power-duration curve. For any micro-cycle, target intensities and durations may be chosen on an individual basis. The model described here is the first conceptual framework of integrating physiologically defined intensities and fatigue related durations to optimize high-performance exercise training.

Keywords: exercise prescription, intensity, duration, endurance exercise, athletes

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INTRODUCTION

The regulation of endurance training is usually based on the prescription of individual exercise intensity zones/domains, (Meyer et al., 2005; Pescatello, 2014, p. 168) whereas, in contrast, exercise duration is rarely prescribed by individual measures and mostly set from personal experience or "usual" settings. Tremblay et al. (2005) critically mentioned that little research tempting to isolate the effect of exercise duration has been done but they suggested a duration threshold for hormonal responses especially for low intensity exercise. This is in line with earlier results by Viru et al. (1996) proposing that in exercise performed below a certain threshold intensity, hormonal responses will only occur after a certain long duration. As the hormonal changes trigger acute and chronic adaptation it is suggested that not only intensity but also the duration for any specific intensity is crucial to induce training effects or to avoid overload (Viru, 1995, p. 1–20). Recently, it was shown by Skovgaard et al. (2016) that muscle PGC-1α mRNA, identified as a key regulator of mitochondrial biogenesis and oxidative genes, did not change significantly after 60 min of endurance exercise in their study. This short duration and a high fitness level did not allow to sufficiently challenge muscle PGC-1α mRNA for the relative low exercise intensity (60% of $VO2_{max}$) applied. However, including high intensity speed endurance exercise provided a stimulus for muscle mitochondrial biogenesis, substrate regulation, and angiogenesis.

Consequently, concerning training effects (Platonov, 1999; Noakes, 2000; Abbiss and Laursen, 2005), concepts integrating the prescription of both intensity and duration within one model are needed with respect to the main aims in endurance training which are to increase maximal oxygen uptake, the maximal sustainable speed, or power (threshold speed), and to increase economy and time to exhaustion (Lundby and Robach, 2015).

Several authors prescribed the distribution of various intensity domains for endurance training (Esteve-Lanao et al., 2005; Seiler and Kjerland, 2006; Seiler, 2010; Stöggl and Sperlich, 2015), but explicit prescriptions of an optimal duration for each individual intensity domain are still missing. Pettitt (2016) recently combined exercise intensity and duration by introducing a critical velocity similar to the critical power concept (Vanhatalo et al., 2011; Poole et al., 2016). The CP model itself is not based on physiological measures, although it seems to have a physiological basis which was shown to be related to the maximal lactate steady state intensity (Jones et al., 2008, 2010). This concept however, does not include a differentiation of all intensity domains (Meyer et al., 2005; Hofmann and Tschakert, 2010) which are known to trigger specific acute physiological responses, which are suggested to be crucial for a successful training adaptation (Hoppeler, 2016). Dekerle et al. (2003) as well as Pringle and Jones (2002) showed that the critical power calculated from a given range of exhaustion time did not correspond to the maximal lactate steady state (mLaSS) similar to Brickley et al. (2002) indicating the need to combine both aspects into one model recently shown by Burnley and Jones (2016).

It is well-prescribed that competitive endurance athletes using the polarization model train up to 13 training sessions per week with an intensity distribution of about 80% of total training volume performed at low intensity and about 20% high-intensity work such as interval training (Esteve-Lanao et al., 2005; Seiler and Kjerland, 2006; Seiler, 2010; Stöggl and Sperlich, 2015). From this point of view, a focus on optimization of both the low intensity-high volume and the high intensity-low volume parts of the training as well as concepts and models to prescribe both intensity and duration including physiologically relevant zones are required. Aim of the paper is to give a theoretical framework prescribing both intensity and duration for endurance training.

PRESCRIPTION OF INTENSITY

The prescription of exercise intensity for endurance-type exercise is usually based on exercise markers from maximal and/or sub-maximal incremental exercise tests (Meyer et al., 2005). Guidelines recommend using percentages of maximal oxygen uptake ($VO2_{max}$), maximal heart rate (HR_{max}), or maximal power output (P_{max}) for setting exercise intensity (Pescatello, 2014, p. 168). However, threshold or turn point concepts are suggested to be the gold standard for exercise intensity prescription in practice (Meyer et al., 2005) although still critically discussed (Mann et al., 2013). Actually, most authors agree to set training intensities by a three phase and two threshold model (Meyer et al., 2005; Hofmann and Tschakert, 2010) indicated by a first lactate (LT_1/LTP_1) or ventilatory (VT_1) and a second lactate (LT_2/LTP_2) or ventilatory (VT_2) threshold or turn point which has been successfully integrated into the practice (Seiler and Kjerland, 2006; Seiler, 2010; Algrøy et al., 2011; Muñoz et al., 2014a,b; Tønnessen et al., 2014, 2015). **Figure 1** shows an example of the time course of selected variables and the according turn points LTP_1/VT_1 and LTP_2/VT_2 for a trained cyclist.

Several variables enable to discern three distinct phases of metabolism and cardio-respiratory responses which allow setting defined intensities for continuous or interval-type exercise (Hofmann and Tschakert, 2010; Tschakert and Hofmann, 2013). According to the lactate shuttle theory (Brooks, 1986, 2009) the first lactate turn point (LTP_1) is defined as the first increase in blood lactate concentration (La) accompanied by a first change of increase in ventilation (VT_1) and distinct changes in other ventilatory variables. The second lactate turn point (LTP_2) is defined as the second abrupt increase in La accompanied by a sharp increase in ventilation (VT_2) and distinct changes in other ventilatory variables (**Figures 1**, **2**). It has to be mentioned that the chosen incremental test protocol influences the accuracy of any threshold determination and the validity to prescribe constant load or intermittent-type exercise. A careful choice of the protocol is accordingly substantial. A detailed discussion of this problem, however, is not within the scope of this article but discussed elsewhere (McLellan, 1985; Amann et al., 2004).

Continuous Exercise

The first and the second turn points are sub-maximal markers from incremental exercise which can be used to prescribe defined exercise workloads with distinct and defined metabolic, cardio-respiratory, and hormonal responses as shown recently by our working group for constant load and matched intermittent-type exercise (Tschakert and Hofmann, 2013; Moser et al., 2015; Tschakert et al., 2015). During exercise below LTP_1, no increase in La above baseline level was detected for constant load exercise, and it was shown recently that this intensity can be sustained for a very long duration of up to 24 h in trained ultra-distance athletes (Pokan et al., 2014). Increasing the workload above LTP_1 leads to an increase in La above baseline, but after several minutes a La steady state is built up. The mLaSS is reached at LTP_2 power output, but this intensity is clearly limited in time (Dittrich et al., 2014) but independent of exercise mode (Fontana et al., 2009), training status, and temperature (Périard et al., 2012). Although

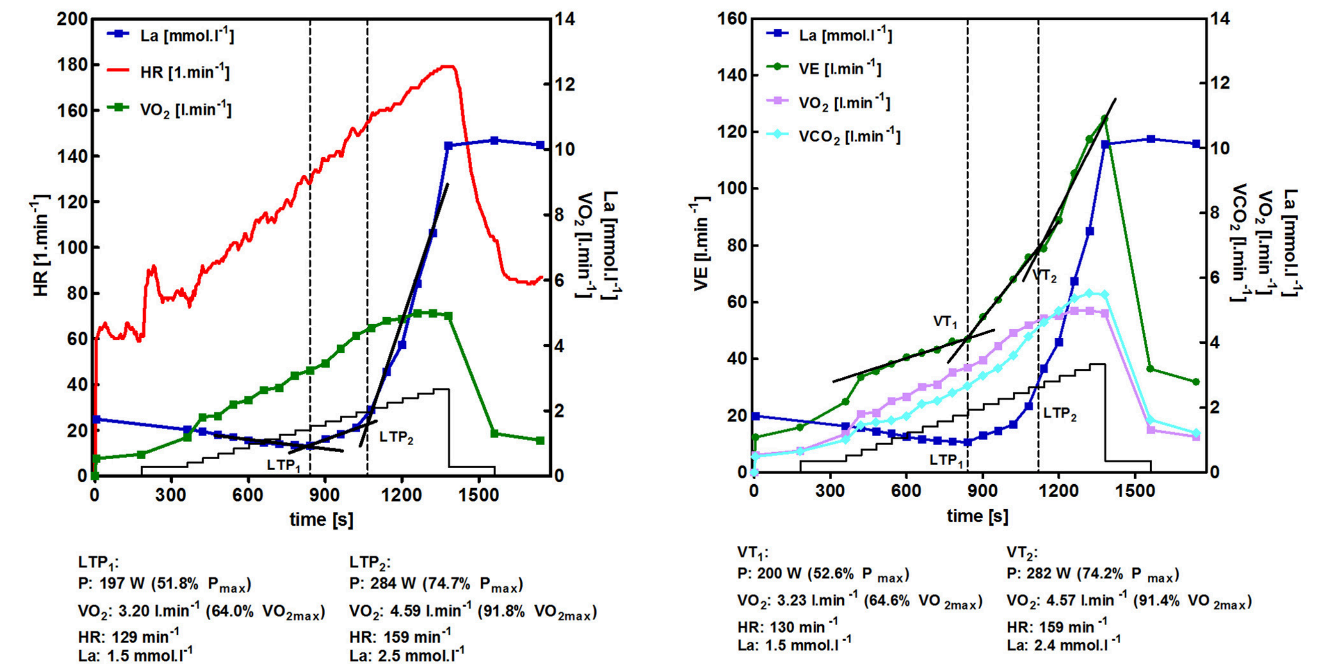

FIGURE 1 | Time course of heart rate (HR), oxygen uptake (VO_2), and lactate (La) as well as the first (LTP_1) and the second (LTP_2) lactate turn point during an incremental cycle ergometer exercise test in a well-trained cyclist (A). Time course of ventilation (VE), oxygen uptake (VO_2), carbon dioxide output (VCO_2), and lactate (La) as well as the first (VT_1) and the second (VT_2) ventilatory turn point during incremental cycle ergometer exercise in a well-trained cyclist **(B)**.

mLaSS intensity can be determined rather precisely, time to exhaustion at the mLaSS still can vary distinctively between athletes. Faude et al. (2017) showed a low reliability of time-to-exhaustion and blood lactate concentration at mLaSS indicating that a precise individual prescription of exercise still remains challenging especially with respect to duration.

Workloads above LTP_2/VT_2 lead to a constant increase in La until the individual level of tolerance has been reached. This is also reflected in the response of adrenaline and noradrenaline (Moser et al., 2015). **Figure 3** shows schematically the time course of La for the three different exercise intensity zones. Percentages of maximal heart rate ($\%HR_{max}$), of maximal oxygen uptake ($\%VO_{2max}$), or % HR reserve (%HRR) as well as % oxygen uptake reserve (VO_2R) are not able to discriminate these phases correctly on an individual basis (Hofmann et al., 2001; Meyer et al., 2005; Scharhag-Rosenberger et al., 2010).

Usually, the first and/or the second turn points (corresponding to the mLaSS) are applied to prescribe exercise intensity limits for prolonged endurance exercise training (Esteve-Lanao et al., 2005; Muñoz et al., 2014a; Tønnessen et al., 2014) whereas the first turn point is rarely investigated (Mann et al., 2013). It is obvious that LTP_2/VT_2 clearly discern between sustainable, metabolically balanced or non-sustainable, not metabolically balanced workloads, whereas during exercise near the first turn point a difference in acute responses can only be detected after a very long duration of exercise (Tremblay et al., 2005). Mostly, these small differences in intensity slightly below or above LTP_1/VT_1 are not detected and recognized by athletes although it might be important with respect to the particular maximal duration, grade of fatigue and the subsequent recovery time which has been described recently by Burnley and Jones (2016). These authors suggested distinct fatigue mechanisms for each intensity domain. A paucity of fatigue-related mechanistic studies was shown for the moderate and high-intensity domains but lee attention has focused on the low intensity part so far. As can be seen in **Figure 3**, an intensity slightly above LTP_1 already increases La which indicates that the critical lactate clearance rate for the working muscle has been exceeded, and therefore, different hormonal and cardio-respiratory responses are suggested for this intensity level (Moser et al., 2015). In very prolonged exercise with blood lactate remaining at resting level throughout exercise it was prescribed that only after several hours fatigue occurs and increases with time until the limit of tolerance (Burnley and Jones, 2016). It has to be mentioned that energy stores play a substantial role regarding the maximal duration until the point of fatigue (Johnson et al., 2004).

Interval Exercise

The prescription of intermittent exercise is somehow more complicated compared to continuous exercise as the number of variables is higher. In addition to the workload intensity for the intervals (P_{peak}), the total duration (t_{total}) (number of intervals), the duration of the single workloads (t_{peak}) as well as recovery intensity (P_{rec}) and duration (t_{rec}) and the corresponding mean load (P_{mean}) have to be considered (Buchheit and Laursen, 2013a,b; Tschakert and Hofmann, 2013). Similar to constant load exercise (CLE), the mean intensity and total duration are main markers of the overall workload, but P_{mean} is influenced by the

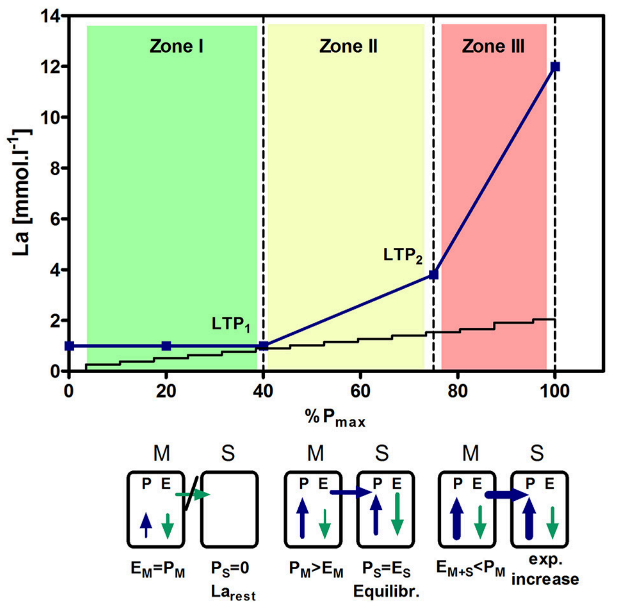

FIGURE 2 | Time course of blood lactate concentration (La) and first (LTP_1) and second (LTP_2) lactate turn points. LTP_1 is the first increase above baseline. Lactate production within the muscle (P_M) is equal to the elimination rate within the working muscle (E_M) and, consequently, no La has to be shuttled to the system (S). La within the system stays at resting level because the critical lactate clearance of the working muscle is not exceeded. This is the first zone which is metabolically balanced at muscle level (M) ($E_M = P_M$). Above LTP_1, blood La increases with increasing workloads. La production within the muscle (P_M) exceeds the muscular rate of La elimination (E_M) and La has to be shuttled to the system (S). Within the system, La from the muscle (P_S) can be eliminated (by resting muscles, heart, brain,...) ($E_S + E_M = P_M$) and La builds up an equilibrium ($P_S = E_S$) at an elevated level, a so called lactate steady state on a systemic level. The critical La clearance rate of the system is not exceeded which gives a metabolically balanced situation (zone II). If the rate of La production within the muscle exceeds the maximal elimination rate of the system and the muscle ($P_M > E_M + E_S$), La increases exponentially without a metabolically balanced situation (zone III). The transition from zone II to zone III is indicated by the LTP_2.

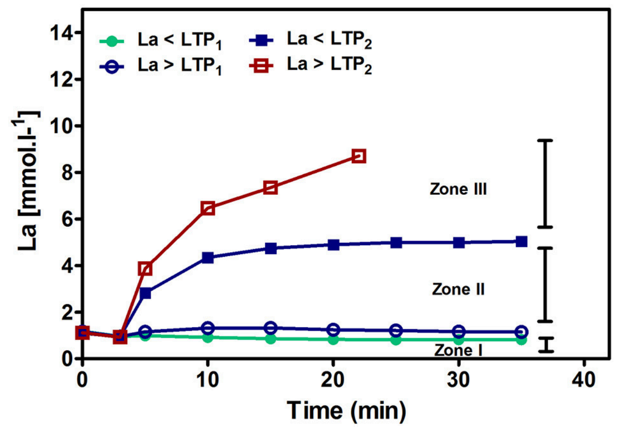

FIGURE 3 | Time course of blood lactate concentration (La) below and above the first (LTP_1) and the second (LTP_2) lactate turn points. Intensities below LTP_1 give a lactate steady state at resting level because the critical lactate clearance rate within the working muscle is not exceeded (zone I). For intensities above LTP_2, some La produced within the muscle is shuttled to the system but La clearance is high enough to establish an equilibrium, the so called systemic La steady state (LaSS) (zone II). Just below LTP_2 the maximal lactate clearance rate, the so-called maximal systemic LaSS is approached. Above LTP_2, no equilibrium can be established and La increases with time with early termination of exercise due to non-sustainable acidosis (zone III).

aforementioned variables with respect to the degree and the kind of fatigue and recovery (Burnley and Jones, 2016). Nonetheless, also for intermittent exercise, intensities (P_{peak}, P_{rec}, P_{mean}) are suggested to be set in relation to sub-maximal (LTP_1/VT_1, LTP_2/VT_2) and maximal markers (P_{max}) from an incremental exercise test: $P_{peak} = P_{max}$, $P_{rec} = \%P_{LTP1}$, $P_{mean} = \%P_{LTP2}$ (Tschakert and Hofmann, 2013).

In addition, we could recently show that aerobic high-intensity interval exercise (HIIE) with short workload durations and P_{mean}-matched constant load exercise produced similar acute metabolic, hormonal and cardio-respiratory responses (Moser et al., 2015; Tschakert et al., 2015). In contrast, HIIE with long workload durations but the same mean load yielded significantly higher acute physiological responses compared to short HIIE and CLE (Tschakert et al., 2015). This indicated that strictly planning interval-type exercise respecting all variables allows the regulation and the predictability of the acute physiological responses (Tschakert et al., 2015). In a recent paper we could show that even with a high-intensity running speed, short 10 s intervals, 20 s passive recovery but a very low mean load below LTP_1, lactate levels were only slightly higher than resting level, and 30 min of exercise was clearly below the maximal duration which was, however, not obtained in this study (Wallner et al., 2014).

Similar to constant load exercise (Chidnok et al., 2012; Soares-Caldeira et al., 2012), the problem arises how to prescribe the optimal total duration (number of intervals) for intermittent exercise to identify optimal adaptation effects for any specific micro-cycle of a training period (Platonov, 1999; Lyakh et al., 2014). As long as there is a metabolically balanced situation (aerobic interval training), we may treat this problem similar to constant load exercise. In case of increasing La (anaerobic interval training), the optimal number of intervals may be set similar as it is performed in resistance-type exercise (Richens and Cleather, 2014). Again there is urgent need to identify any markers of optimal duration for both constant load and interval-type exercise. Burnley and Jones (2016) highlighted that the power-duration relationship exists not only for constant-power laboratory-based exercise, but also for variable-paced, self-paced, and intermittent or stochastic exercise, which more closely reflects the "real-world" athletic performance.

PRESCRIPTION OF DURATION

It is a fact that any certain intensity has its own critical time limit which is dependent on the type of exercise and the kind of athletes, but may be used as an individual diagnostic tool to prescribe exercise duration (Vanhatalo et al., 2011; Pettitt,

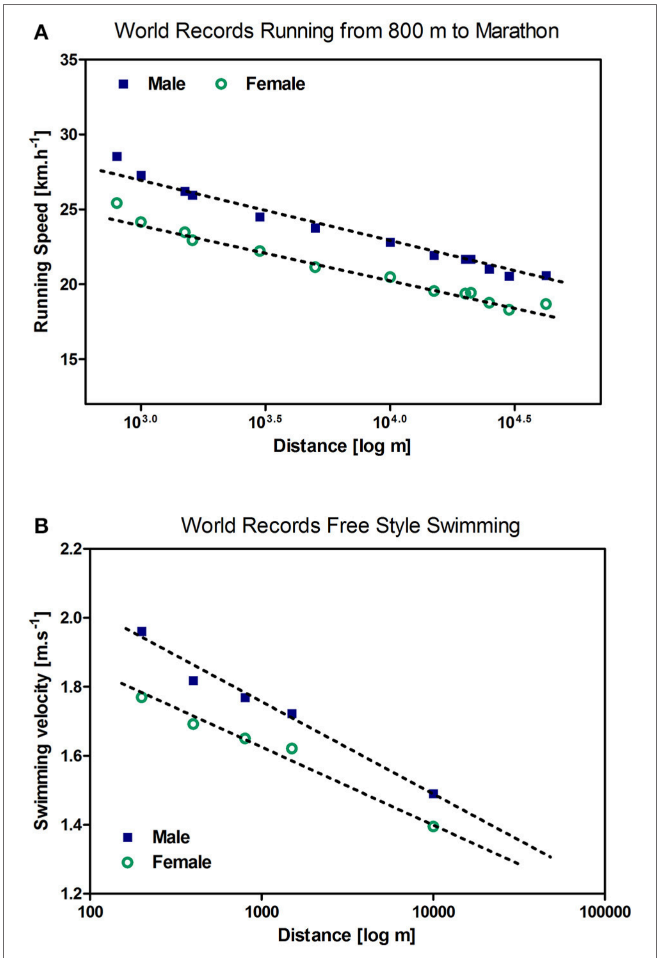

FIGURE 4 | Speed-duration relationship of endurance-type world records in running from 800 m to marathon race distance (A) and swimming **(B)** was shown to be linear in a logarithmic scale for male and female athletes.

2016; Poole et al., 2016). **Figure 4A** shows the running speed for all endurance-type world records in continuous running from 800 m to marathon distance which has been described as a most perfect logarithm relationship for both men and women (Nikolaidis et al., 2017). A similar relationship can be shown for free style swimming (**Figure 4B**). The relationship between speed and distance is linear applying a logarithmic x-axis within this wide range of race distances. It is obvious that no speed-distance pairs above the linear line are possible (Burnley and Jones, 2016). This speed-distance or power-duration relationship can therefore be applied to detect the maximal speed or power output for any distance or duration but, no less importantly, to detect any maximal duration or distance for an arbitrarily chosen speed or power on an individual basis. Additionally, independent of the chosen intensity, this concept allows setting a targeted duration (% of maximal duration) for endurance exercise training with respect to improvement, maintenance or recovery purposes. To regulate these distances we apply the concept of Platonov (1999) who differentiated four domains of durations with selective adaptation (Viru, 1995, p. 251). This author suggested "very heavy maximal," "heavy sub-maximal," "moderate," and "low" workloads with respect to duration, but independent of the chosen intensity (**Table 1**).

Platonov (1999, p. 51) suggested that only "maximal exercise" (75–100% of the maximal duration until clear fatigue and loss of performance) induces distinct adaptation processes. This maximal exercise needs long recovery of about 48 h and longer but induces considerable performance increments (Kenttä and Hassmén, 1998; Issurin, 2009) (**Figure 5**) indicated by hormonal responses and signal-cascades yet not fully understood (Russell et al., 2013; Hoppeler, 2016; Kirby and McCarthy, 2016). Shortening the duration to 60–75% of the maximal duration until clear fatigue with the same intensity only leads to a compensated fatigue (some signs of fatigue which can be compensated without a loss in performance) which reduces recovery duration to half of the maximal exercise domain (about 24 h). The moderate workload is suggested between 20 and 60% of the maximal duration which does neither induce a compensated nor a clear fatigue and, therefore, does not increase performance but rather stabilizes it. Lastly, low workload defined as duration of less than 20% of maximal duration (again with the same intensity) induces regeneration and maintains exercise performance. **Figure 6** shows an example of the recovery of heart rate variability (HRV) after maximal, sub-maximal, moderate, and low duration exercise with the same intensity applied (unpublished results). HRVwas shown to be sensitive for intensity and duration of exercise (Kaikkonen et al., 2010; Myllymäki et al., 2012).

From this concept (Platonov, 1999, p. 51; Viru, 1995, p. 251), we assume that for any single intensity within the three different intensity domains (Zone I: below LTP_1/VT_1; Zone II: between LTP_1/VT_1 and LTP_2/VT_2; Zone III: above LTP_2/VT_2), we may chose four different duration domains with clearly distinct adaptation effects on various physiological processes and exercise performance. To prescribe these duration domains one needs the maximal duration for at least 2–3 different intensities to draw the power-duration relationship as can be seen in **Figure 7** which shows the same athlete as **Figure 1**.

Model to Combine the Prescription of Both Intensity and Duration

Earlier approaches such as the model from Garcin and Billat (2001) applied a perceived exertion scale to attest both intensity and duration, but the optimal duration may not be obtained from this model. As can be seen in **Figures 7**, **8**, the power output (or speed) to time (or distance) relationship allows discerning these specific durations for any intensity of interest by using four different duration domains according to Platonov (in (Viru, 1995), p. 251). As shown in **Table 1**, zone 1 is defined as low, zone 2 as moderate, zone 3 as sub-maximal, and zone 4 as maximal workload each producing different states of fatigue and, consequently, different effects of adaptation, which is in line with recent data from Tremblay et al. (2005). These authors showed a duration threshold for various hormone responses for a comparable low intensity of 50–55% VO_{2max} whereas a longer duration induced a favorable hormone profile

TABLE 1 | Definition of specific duration domains for endurance-type exercise (modified from Platonov, 1999).

Workload	Phase	Duration	Targets
Low	1st phase of stable performance	15–20% of maximal duration until clear fatigue	Maintaining exercise performance and accelerated recovery
Moderate	2nd phase of stable performance	20–60% of maximal duration until clear fatigue	Maintaining exercise performance
Sub-maximal	Phase of compensated fatigue	60–75% of maximal duration until clear fatigue	Stabilization and moderate increases in performance
Maximal	Phase of clear fatigue	75–100% of maximal duration until clear fatigue	Distinct increases in performance

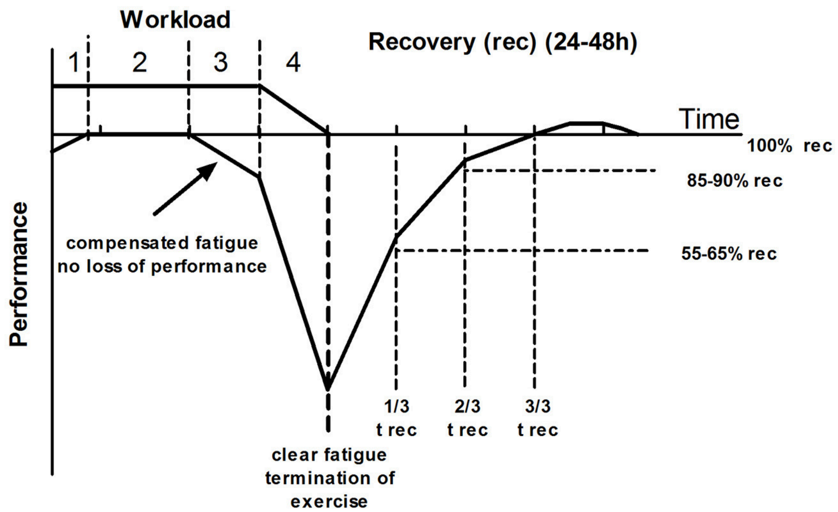

FIGURE 5 | Relationship between duration of exercise and fatigue (modified from Platonov, 1999). There is a certain duration for each intensity leading to distinct grade of fatigue which terminates exercise (4), prolongs recovery times and increases "super-compensation" with increased performance. Reducing the duration to less than 75% of the maximal duration does not induce distinct but compensated fatigue without a loss in performance (3) and, consequently, a much shorter recovery time and less if any "super-compensation." Reducing duration to less than 60% of the maximal duration (2) does not induce any fatigue and, therefore, does not increase performance, but rather stabilizes the given performance level. A duration less than 20% of the maximal duration is just a functional stimulation suggested adequate for regeneration.

which was suggested to support the mobilization of fuels for recovery and restoration of glycogen stores. In this combined exercise prescription model, the setting of work intensities should also be individualized and physiologically based by using turn point intensities as discerning markers for distinctly different metabolic, hormonal and cardio-respiratory responses (Tschakert and Hofmann, 2013; Moser et al., 2015).

This concept (**Table 1** and **Figure 8**) enables athletes and coaches to fine-tune training volume and/or intensity to further optimize training processes which is of particular relevance when the limits of tolerance are reached. In addition, it allows a retrospective analysis of distances covered with given intensities in the past.

DISCUSSION AND CONCLUSIONS

The concept to combine turn point derived intensities and optimized durations may be specifically interesting with respect to the new polarized training concept (Seiler and Kjerland, 2006; Seiler, 2010; Muñoz et al., 2014a,b; Tønnessen et al., 2014) where 80–90% of training volume is set below LTP_1/VT_1 and up to 22% above LTP_2/VT_2 with very low volumes between both thresholds. It is, however, important to note that some authors also use fixed reference values for lactate such as 2 and 4 $mmol.l^{-1}$ (Seiler and Kjerland, 2006; Guellich et al., 2009; Orie et al., 2014) which may overestimate the volume especially for the low intensity volumes. Our own results showed that La at LTP_1 was found at 1.2–1.6 $mmol.l^{-1}$ (Hofmann et al., 1997, 2001). An individual and accurate intensity prescription is crucial even at low power outputs near LTP_1 since allowing intensities just 10% above LTP_1 definitely shortens the time to clear fatigue by ~40% (**Figure 8**). As a consequence, high-volume training set above LTP_1 may get too close to a fatigue state that avoids repeating high volumes on a regular daily basis. In addition, for low intensity exercise training, it is usually NOT intended to reach maximal duration (t_{max}) but to apply a certain percentage of t_{max} (**Table 1**) in order to avoid fatigue and to guarantee the ability to repeat high volumes of training on a daily basis. However, we like to point out that dependent on the aim of a specific training period specific types of micro-cycles need to be structured combining exercise type, intensity, and duration.

Beside the attractiveness of the concept, several open questions and limits have to be addressed. Firstly, the chosen

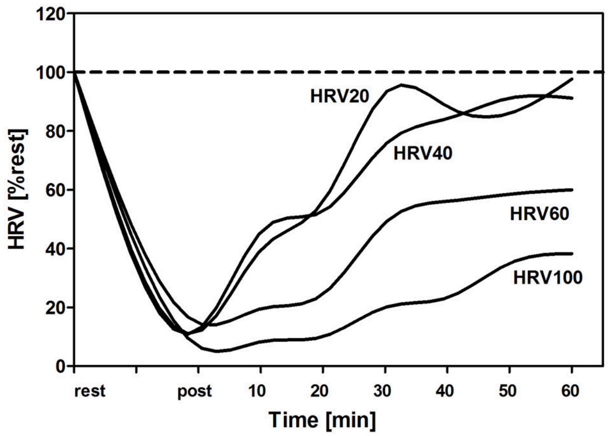

FIGURE 6 | Relative changes of heart rate variability markers (%HRV) during constant load exercise just below the second lactate turn point with different duration of the maximal sustainable distance (100%). It can be seen that recovery of the HRV is dependent on % maximal duration with early recovery at low to moderate distances (20, 40%) according to Platonov (1999).

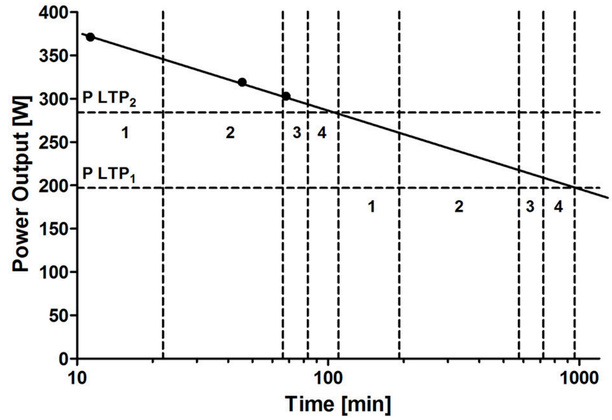

FIGURE 8 | Maximal and optimal (% of maximal) duration for exercise intensities at LTP_1 and LTP_2 in a well-trained cyclist applying the modified concept of Platonov (1999). For any specific metabolic, hormonal or cardio-respiratory target intensity ($<LTP_1/VT_1$; between LTP_1/VT_1 and LTP_2/VT_2; $> LTP_2/VT_2$), the optimal duration with respect to the four workload domains "low" (1), "moderate" (2), "sub-maximal" (3), and "maximal" (4) may be derived from this graph of the maximal intensity-duration relationship.

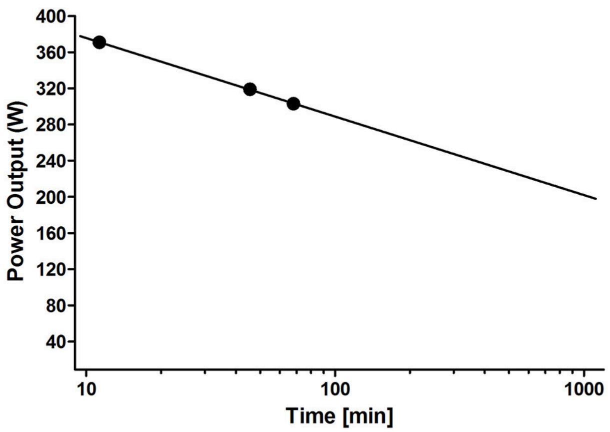

FIGURE 7 | Example of exercise intensity-duration relationship in a single well-trained cyclist. As described in **Figure 1**, for any individual athlete, a plot of maximal speed and distance relationships can be drawn describing the maximal distance for any specific velocity or power output or the maximal velocity or power output for any chosen distance. According to the modified concept from Platonov (1999), these individual draws allow to prescribe the optimal distance (% of maximal duration) for selected intensities for various endurance-type training situations. To prescribe both intensity and duration on an individual basis, this concept needs to be combined to the usual sub-maximal performance diagnostic markers such as LTP_1/ VT_1 and LTP_2/VT_2.

percentages of maximal duration are just marginally evidenced. To discern the low (regenerative) zone from a moderate zone without fatigue, a zone with compensated fatigue and finally zone 4 with clear fatigue needs to be taken with caution. Carefully conducted studies and retrospective analysis of distances covered at defined intensities are needed to identify the stability or variability of these percentages for athletes with different age, training status and sex, and individual physiological markers are needed to guide the training. As could be shown in a pilot test (**Figure 6**), heart rate variability might be a potential parameter to identify these cut-off points for duration as discussed recently (Kaikkonen et al., 2010; Saboul et al., 2016). Additionally, ratings of perceived exertion (RPE) scales may be helpful to identify these reference markers on a daily individual basis (Garcin and Billat, 2001; Seiler and Sjursen, 2004; Coquart et al., 2012).

A second important limit is the method to derive the power-duration or velocity—distance relationship. To obtain a valid regression line, data points must be obtained from highly motivated athletes from competitions. However, maximal performance changes during the training year due to periodization will make it a bit more difficult to obtain optimal distances throughout the year. Additionally, not all sports allow obtaining these markers under comparable and possibly standardized conditions such as in cycling or on-snow cross-country skiing. Semi-specific tests such as ergometer or ski-roller tests may help to overcome this problem.

A third limit may be the idea to maximize volumes by reducing intensity below LTP_1/VT_1. Although athletes may withstand such volumes from an acute metabolic state of view, some long-term problems such as orthopedic complaints (arthrosis, stress fractures) as well as disturbances in energy or fluid supply may arise from such as concept (Noakes, 2000; Cymet and Sinkov, 2006; Krampla et al., 2008; Weber, 2009; Warden et al., 2014).

Despite those limits, this concept gives a solid theoretical framework that allows optimizing both intensity and duration of the whole spectrum of endurance training load for the first time. It may help to improve exercise training for top level performance even though it is already close to the limits of tolerance for the human body.

ETHICS STATEMENT

This methodological consideration included a single pilot tests which were not part of a formal study but a proof of principle determination of markers from standard performance diagnostic tests which was performed in accordance with the recommendations of Declaration of Helsinki. The subject gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

PH: Author wrote the manuscript, draw the figures, and graphs. GT: Author contributed equally in writing the manuscript.

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Training Intensity Distribution and Changes in Performance and Physiology of a 2nd Place Finisher Team of the Race across America Over a 6 Month Preparation Period

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Aim: To monitor the training intensity distribution (TID) and the development of physiological and performance parameters.

Methods: During their preparation period for the RAAM, 4 athletes (plus 1 additional backup racer) performed 3 testing sessions; one before, one after 3, and one after 6 months of training. VO_{2max}, maximal rate of lactate accumulation (dLa/dt_{max}), critical power, power output at lactate minimum ($MLSS_P$), peak and mean power output during a sprint test, heart rate recovery, isometric strength, jumping height, and body composition were determined. All training sessions were recorded with a power meter. The endurance TID was analyzed based on the time in zone approach, according to a classical 3-zone model, including all power data of training sessions, and a power specific 3-zone model, where time with power output below 50% of $MLSS_P$ was not considered.

Results: The TID using the classical 3-zone model reflected a pyramidal TID (zone 1: 63 ± 16, zone 2: 28 ± 13 and zone 3: 9 ± 4%). The power specific 3-zone model resulted in a threshold-based TID (zone 1: 48 ± 13, zone 2: 39 ± 10, zone 3: 13 ± 4%). VO_{2max} increased by 7.1 ± 5.3% ($P = 0.06$). dLa/dt_{max} decreased by 16.3 ± 8.1% ($P = 0.03$). Power output at lactate minimum and critical power increased by 10.3 ± 4.1 and 16.8 ± 6.2% ($P = 0.01$), respectively. No changes were found for strength parameters and jumps.

Conclusion: The present study underlines that a threshold oriented TID results in only moderate increases in physiological parameters. The amount of training below 50% of MLSSp (∼28% of total training time) is remarkably high. Researchers, trainers, and athletes should pay attention to the different ways of interpreting training power data, to gain realistic insights into the TID and the corresponding improvements in performance and physiological parameters.

Keywords: critical power, VO_{2max}, maximal rate of lactate accumulation, MLSS, lactate minimum intensity, ultra-endurance performance

INTRODUCTION

The Race Across America (RAAM) is an annual 4800 km non-stop cycling race from the west coast of America to the east coast. The physiological and environmental challenges encountered by the athletes participating in this event are numerous: insufficient energy intake (Knechtle et al., 2005; Hulton et al., 2010), sleep deprivation (Hulton et al., 2010; Lahart et al., 2013) and tough climate conditions like extreme heat in the desert or very high humidity resulting in a decline in performance due to dehydration (Bowen et al., 2006; Paulin et al., 2015). Additionally, over 30,000 m of altitude difference and the corresponding time under hypoxic conditions make the event one of the toughest bike races in the world and the unofficial world championship of ultra-endurance cycling. The race can be performed as a team event, with 2, 4, or 8 racers as a relay team or solo.

The performance requirements for a team relay in the RAAM can be described as an enormous number of individual time trials, interspersed by longer and shorter phases of recovery, depending on the team tactics. The physiological load can, therefore, be compared to the bike split in triathlon events, where performance (after preload by the swim split) is ideally as high as possible without impeding the following run split. Under ideal conditions, each team member in a 4 person relay team would have to cover 1200 km on the bike as fast as possible.

Concerning the physiological prerequisites, Laursen et al. (1999) described a RAAM relay team with 4 racers, finishing in fourth place with a mean maximal oxygen uptake (VO_{2max}) of 71.5 $mL \cdot min^{-1} \cdot kg^{-1}$,while a solo racer winning the RAAM was described by Ice et al. (1988) with a VO_{2max} of 79.6 $mL \cdot min^{-1} \cdot kg^{-1}$. These values correspond roughly to the range of VO_{2max} values for professional cyclists from 69.7 $mL \cdot min^{-1} \cdot kg^{-1}$ to 84.8 $mL \cdot min^{-1} \cdot kg^{-1}$summarized by Padilla et al. (1999). However, Faria et al. (2005) showed in their review of cycling physiology, that VO_{2max} alone is neither a good predictor of endurance performance nor a valid distinction between elite and amateur cyclists. Lactate threshold (LT) might be more suitable as a predictor of endurance performance since it was the single variable that correlated best with time trial performance ($r = 0.86$, $p = 0.01$) in the study of Støren et al. (2013). This might be associated with the findings of Jacobs et al. (2011), who demonstrated that endurance performance among highly trained cyclists correlated with skeletal muscle oxidative capacity, accounting for 47% of the variation in 26 km time trial performance. However, no previous study did report comprehensively on the development of aerobic [e.g., VO_{2max}, maximal lactate steady state (MLSS)] and anaerobic parameters [e.g., maximal rate of lactate accumulation (dLa/dt_{max}), maximal voluntary contraction (MVC)] in combination with performance measures [peak power output (PPO), sprint PPO, sprint mean power output (MPO), critical power (CP)] over the course of a preparation period for an ultra-endurance cycling race.

On the topic of training to optimize performance for such extreme endurance challenges, different information can be found in scientific literature. Stöggl and Sperlich (2015) proposed different concepts of training intensity and volume distribution (TID) in the physical conditioning of endurance athletes: (1) high-volume low-intensity training (HVLIT), (2) training at or near the lactate threshold (THR), (3) low-volume high-intensity interval training (HIT), (4) "pyramidal" (PYR) TID consisting of high volume of HVLIT, medium volume of THR, and small volume of HIT, (5) as well as the combination of HVLIT and HIT, named "polarized" training (POL).

There are a number of prospective and intervention studies in cycling (Neal et al., 2013), running (Esteve-Lanao et al., 2007; Muñoz et al., 2014), different endurance disciplines (Stöggl and Sperlich, 2014), as well as retrospective studies in speed skating (Yu et al., 2012), running (Billat et al., 2001), and cross-country skiing (Seiler and Kjerland, 2006), reporting the superiority of a POL TID compared to other TIDs.

However, there are also many retrospective studies, generally reporting a PYR TID for endurance athletes in running (Esteve-Lanao et al., 2005), cycling (Luciá et al., 2000; Schumacher and Mueller, 2002; Zapico et al., 2007), and triathlon (Neal et al., 2011). In a recent review, it was summarized that most retrospective studies on well-trained athletes report on PYR TID, although some world-class athletes performed POL TID during certain phases of the season (Stöggl and Sperlich, 2015). Sandbakk et al. (2016), Tønnessen et al. (2014), and Guellich et al. (2009) reported a general focus on HVLIT TID in the preparation period, which became more polarized in the competition period of world/national class cross-country skiers, biathletes, and young world-class rowers.

Most studies reporting TID used the heart rate (HR) or the rate of perceived exertion (RPE) to determine training time in different intensity zones. To the best of our knowledge, there are no studies using power output for the determination of TID. The ability to accurately quantify the mechanical work during training makes cycling unique in allowing such insights into the demands of sporting preparation. Power output as a marker of the external load is zero in phases like downhill sections or during coasting, but the internal load represented by the HR might still appear higher (Halson, 2014), resulting in a "smoothing effect." Especially very short high-intensity accelerations (e.g., initial pedal strokes or short intervals), as well as abrupt reduction of external load, will not be reflected by the HR. Additionally, Seiler and Kjerland (2006) demonstrated very big differences in TID between the total time-in-zone approach and the session-goal method. Many factors may influence the relationship between workload and HR (Buchheit, 2014), and day-to-day variation in HR was shown to be approximately 6.5%, which might influence the analysis of HR data and consequently the time spent in each zone (Bagger et al., 2003). However, Davies and Knibbs (1971) found, that an intensity of at least 50% of VO_{2max} is necessary to result in performance enhancements. This raises the question how TID (time in each zone in a 3 zone-model) based on power data might change: 1. if all power data of training are included in the analysis and are assigned to one of the 3 zones, or 2. if power data below a certain threshold are excluded from the analysis.

We accompanied 6 months of preparation time of a 4 person RAAM team (plus 1 additional backup racer). They later finished the actual race in second place. All athletes were amateurs, and their training time was restricted by social and environmental conditions. The first aim of this study was to add a more detailed physiological and performance profile for long-distance cyclists over the course of their preparation period, including not only aerobic (VO_{2max}, MLSS, CP, PPO), but also anaerobic (dLa/dt_{max}, sprint PPO, MPO, MVC) measurements. The second aim was to analyze which of the physiological variables (VO_{2max}, MLSS, dLa/dt_{max}) might correlate with performance (CP, sprint MPO), including the values of all three testing sessions, in order to see which of the laboratory parameters might be useful to predict performance. The third aim was to examine the composition of the training load based on power data with regards to TID. More specifically, changes in the TID are compared in two conditions: when all power data are included, or when power data below a certain threshold are eliminated.

METHODS

Subjects

Four male experienced cyclists and triathletes (more than 15 years of regular endurance training) and one backup athlete (45 ± 6.5 years; 182.2 ± 8.9 cm; 79.5 ± 6.6 kg) in preparation for the RAAM volunteered to participate in this study over 6 months. The preparation period started after the offseason. During that offseason athletes had a mean training time of ~8 h per week, consisting of cycling, running and swimming. The study protocol was approved by the University's ethics review board and is in accordance with the declaration of Helsinki. Each subject gave it's written informed consent and was informed about possible risks of participation.

Design

Each athlete underwent three single day testing sessions: The first at the beginning of the preparation period, the second after 3 months of training (phase 1) and the third at the end of the 6 months training period (phase 2), 2 weeks before the race. Each diagnostic session was completed in the same manner at the same time of day. Prior to performance testing, the subject's body mass and lean body mass were measured using a four-electrode bioimpedance body scale (BC 418 MA, Tanita Corp., Tokyo, Japan). Performance testing consisted of jump and strength tests, followed by endurance tests on a cycle ergometer. Subjects were instructed to arrive in the laboratory in a rested, 2 h postprandial and fully hydrated state. They were ordered to avert strenuous exercise for at least 24 h before each test. The order of the tests was kept identical for each individual in the following order. Between the different tests, adequate resting time was ensured.

Squat Jump (SJ) and Counter Movement Jump Test (CMJ)

For the SJ, the subjects were instructed to place the hands on the hips and to lower the hip into a squat position with a knee angle of 90°. Out of this position they had to jump with both legs for maximal height. For the CMJ, the subjects were instructed to place the hands on the hips and to lower the hip dynamically down to a self-selected level before jumping with both legs for maximal height. Hands remained on the hips for the entire movement in both tests to eliminate any influence of the arm swing. Flight time was measured using the Optojump (Microgate Srl, Italy) system, which calculated the jump height. Subjects performed three SJ and three CMJ and the maximal jump height was taken for later analysis (Brown and Weir, 2001).

Strength-Tests

Maximal voluntary isometric strength (MVC) was tested with both legs on a leg press (LP), a leg extension (LE), and a leg curl (LC) machine (Edition-Line, gym80, Gelsenkirchen, Germany), which were equipped with the digital measurement technique Digimax (mechaTronic; Hamm, Germany) to make measurements of force-time and velocity-time variables (5 kN strength sensor type KM1506, distance sensor type S501D, megaTron; Munich, Germany) with the included software IsoTest and DynamicTest 2.0, as described previously (Wahl et al., 2016). The sensors were installed in line with the steel band of the machines that lifts the weight plates. Maximum force relative to body weight was calculated for statistical analysis and data presentation. Subjects performed three trials of each test, and the maximal value was taken for later analysis.

Cycling-Tests

All tests were performed on an SRM Ergometer (Schoberer Radmesstechnik, GmbH, Germany, Jülich), with seat and handlebar height kept identical for each subject throughout all tests.

Sprint-Test

After an initial warm-up at 2 $W\cdot kg^{-1}$ for 10 min, followed by 5 min of passive rest, a 15 s all-out sprint test was performed in an isokinetic mode set to a cadence of 120 rpm. The subjects performed the test in a sitting position on the ergometer and were verbally encouraged to achieve maximal power output throughout the test. Afterward, peak power (sprint PPO) and mean power (sprint MPO) were determined. Capillary samples from the earlobe were collected before and in minute intervals (1′–10′) after the test to determine the "maximal rate of lactate accumulation (dLa/dt_{max})" according to Heck et al. (2003) and Hauser et al. (2014a):

$$dLa/dt_{max}\,(mmol\cdot L^{-1}\cdot s^{-1}) = ([La]_{max} - [La]_{rest})\,(t_{exerc} - t_{alac})^{-1}$$

where $[La]_{max}$ ($mmol\cdot L^{-1}$) = maximal lactate concentration after the exercise; $[La]_{rest}$ ($mmol \cdot L^{-1}$) = lactate concentration before exercise; t_{exerc} (seconds) = duration of exercise; t_{alac} (seconds) = period at the beginning of exercise for which (fictitiously) no lactate formation is assumed. The t_{alac} for each subject was set as the time to sprint PPO (seconds).

VO_{2max}-Test

After the sprint test and additional 10 min of recovery, the athletes performed a maximal incremental exercise test (initial load 100 W + 20 W 1 min^{-1}) until exhaustion to determine the VO_{2max} and the corresponding workload (PPO). Heart rate (Polar, Kempele, Finland), VO_2 and carbon dioxide output (VCO_2) (Cortex Metalyzer II, Leipzig, Germany) were continuously measured during the test.

Afterward, the VO_{2max} and dLa/d_{tmax} were used to calculate the maximal lactate steady state ($MLSS_c$) and the lactate turn point 1 (LT1) according to Hauser et al. (2014a).

Lactate-Minimum-Test (LMT)

A modified lactate minimum test (Knöpfli-Lenzin and Boutellier, 2011) was performed exactly 7 min after finishing the VO_{2max} test. After these 7 min of passive recovery, RPE, lactate and heart rate were measured. The drop in heart rate within this time was used to calculate a heart rate recovery index (HRR). Subjects started a second incremental test, beginning with a workload 50 W below the $MLSS_c$. The workload was increased by 10 w every 90 s, until complete exhaustion. Heart rate (Polar, Kempele, Finland) was continuously measured during the test, RPE and lactate samples were obtained out of the earlobe at the end of each step. Power output at the step which elicited lactate minimum (LM) was considered as maximal lactate steady state power ($MLSS_P$), according to Knöpfli-Lenzin and Boutellier (2011).

Short Power-Profile

Besides the laboratory measurements, the athletes underwent 3 mean maximal power (MMP) tests in the field over the duration of 2, 5, and 10 min. The MMP tests were each done on different days around the laboratory measurements. The results were used to calculate critical power (CP) according to Monod and Scherrer (1965).

Training Data

Training mainly consisted of endurance training on the bike. Additionally, athletes carried out individual core stability training, which was not recorded. Endurance training data of the subjects were captured using wireless SRM Cranks (Schoberer Radmesstechnik, GmbH, Germany, Jülich) and the Powercontrol 8 head unit (Schoberer Radmesstechnik, GmbH, Germany, Jülich), saving power data in 1-s intervals for later analysis.

The aggregation of the raw data was done in SRM Win 6.42.18 (Schoberer Radmesstechnik, GmbH, Germany, Jülich), further analysis was performed in Microsoft Excel 2010 (Microsoft Corporation, Redmond, USA) and Statistica 7.1 (StatSoft Inc., Tulsa, USA).

Power data were retrospectively analyzed and were used to determine the percentage of training time spent in each of three training zones for each individual training session.

The classical 3-zone model was defined as follows: zone 1 (below the calculated first rise of lactate/LT1, Hauser et al., 2014a), zone 2 (between LT1 and $MLSS_P$), and zone 3 (above $MLSS_P$). The average training time in each zone for all sessions of each subject was then determined according to Seiler and Kjerland (2006). Additionally, a power specific 3-zone model was defined by deleting all time with power output below 50% of $MLSS_P$, in order to reduce the impact of coasting phases and similar events on the TID: zone 1 (between 50% of $MLSS_P$ and LT1, Hauser et al., 2014a), zone 2 (between LT1 and $MLSS_P$) and zone 3 (above $MLSS_P$). Training zones were adjusted after each testing session according to the changes in LT1 and $MLSS_P$ (**Table 1**). Individual race data were retrospectively analyzed for each of the 4 racers (time, distance, altitude difference, average relative power output, average power output, average power output in percent of $MLSS_P$, average power output in percent of LT1, and average cadence).

TABLE 1 | Changes of power based training zones over the course of the preparation period for RAAM.

Test Nr.	1	2	3
Zone 1	0/136* ± 24–190 ± 42	0/141* ± 17–197 ± 37	0/146* ± 25–215 ± 42
Zone 2	191 ± 51–272 ± 48	198 ± 41–282 ± 34	216 ± 51–292 ± 50
Zone 3	>273 ± 48	>283 ± 34	>293 ± 50

**lower limit of zone 1 for the power specific 3-zone model.*

Statistical Analysis

For all statistical analysis of the data Statistica (Version 7.1, StatSoft Inc., USA) software package for Windows® was used. Descriptive statistics of the data are presented as means ± standard deviation (± SD). Data were tested via skewness and kurtosis test for normal distribution. Indices smaller than 2 were considered to be normal distributed (Vincent, 2005). ANOVA repeated-measures with Bonferroni post-hoc test was used to compare the three testing sessions and the percentage of training time in each zone for each of the 6 months for both TID models. Statistical differences were considered to be significant for $p < 0.05$. The relationship between different parameters was investigated with Pearson's correlation coefficient. For these correlation analyses, all three time points were included. Cohen's effect size (d) was calculated for the comparison of all tests with each other. The thresholds for small, moderate, and large effects were defined as 0.20, 0.50, and 0.80, respectively (Cohen, 1988; Wahl et al., 2014).

RESULTS

The decrease in body mass during the total training period nearly reached statistical significance ($-2.6 \pm 2.3\%$, $P = 0.07$, $d = 0.29$). Body fat was significantly reduced by $-28.7 \pm 19.5\%$ ($P = 0.01$, $d = 1.91$) as shown in **Figures 1A,B**.

Strength-Tests

There was no significant change in relative leg curl MVC ($P = 1.0$, $d = 0.06$), relative leg extension MVC ($P = 1.0$, $d = 0.46$) and leg press MVC ($P = 1.0$, $d = 0.06$). Jumping height in the CMJ ($P = 1.0$, $d = 0.15$) and in the SJ ($P = 1.0$, $d = 0.16$) changed not significantly (**Table 2**).

Sprint-Test

The decreases in the relative PPO and MPO in the sprint nearly reached statistical significance [PPO: $-3.2 \pm 2.7\%$, $P = 0.06$, $d = 0.25$ (**Figure 3A**) and MPO: $-3.6 \pm 4.1\%$, $P = 0.06$, $d = 0.45$ (**Figure 3B**)].

dLa/dt_{max} decreased significantly by $-16.3 \pm 8.1\%$ ($P = 0.03$, $d = 0.73$), relative $dLa/dt_{max}\ kg^{-1}$ decreased significantly by $-16.5 \pm 6.7\%$ ($P = 0.02$, $d = 0.67$) as shown in **Figure 3C**. A

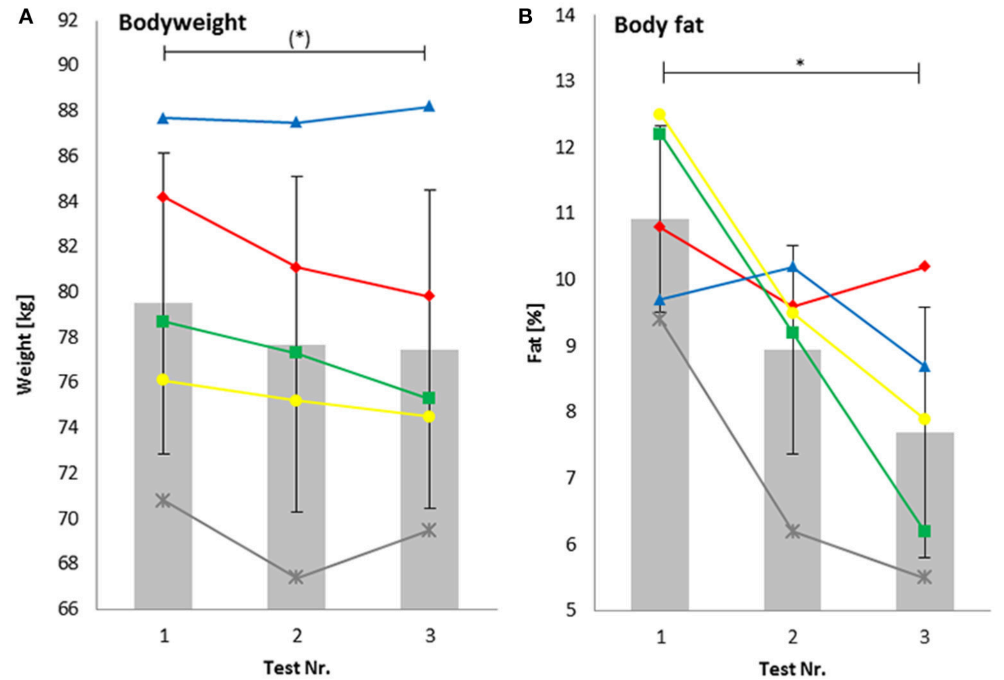

FIGURE 1 | Bodyweight (A) body fat **(B)**. *Significant difference; (*) values nearly reached statistical significance ($P = 0.07$).

TABLE 2 | Maximal isometric strength (ISO MAX) and jump performance.

	Test Nr.	1	2	3
ISO MAX	Leg Press [n·kg^{-1}]	52.0 ± 12.1	43.9 ± 9.9	52.8 ± 17.0
	Leg Extension [n·kg^{-1}]	28.5 ± 2.9	28.0 ± 3.0	29.84 ± 3.2
	Leg Curl [n·kg^{-1}]	16.3 ± 1.0	16.5 ± 0.7	16.3 ± 1.2
Jumps	Squat Jump [cm]	31.68 ± 5.97	32.62 ± 7.58	32.02 ± 5.76
	CMJ [cm]	32.68 ± 6.43	34.04 ± 8.47	33.00 ± 6.89

high correlation was found between relative MPO in the sprint and relative dLa/dt_{max} ($r = 0.85$, $P < 0.001$).

VO_{2max}-Test

The increase in relative VO_{2max} in the time course of the 6-month preparation phase nearly reached statistical significance ($7.1 \pm 5.3\%$, $P = 0.06$, $d = 0.69$) (**Figure 2A**). Relative peak power output in the ramp test significantly increased by $9.5 \pm 7.1\%$ ($P = 0.02$, $d = 0.71$) (**Figure 2B**). The drop in heart rate during 7 min of passive recovery showed no significant changes ($-14.4 \pm 17.2\%$, $P = 0.13$, $d = 0.74$) (**Figure 3D**), as well as peak heart rate in the ramp test (174 ± 10 to 173 ± 9 bpm).

Lactate-Minimum-Test (LMT)

The relative $MLSS_P$ increased significantly by $10.3 \pm 4.1\%$ ($P = 0.01$, $d = 0.61$) similar to the relative $MLSS_c$, which increased significantly by $13.3 \pm 5.5\%$ ($P = 0.008$, $d = 1.56$) (**Figures 2C,D**). There was a high correlation of relative $MLSS_c$ and the relative power output at $MLSS_P$ ($r = 0.94$, $P < 0.001$). Relative $MLSS_P$ showed a high positive correlation with relative VO_{2max} ($r = 0.92$, $P < 0.001$) and a negative correlation with absolute dLa/dt_{max} ($r = -0.78$, $P < 0.001$).

Short Power-Profile

Relative MMP tested in the field over a duration of 2 min increased significantly by $18.7 \pm 13.4\%$ ($P = 0.01$, $d = 1.81$), 5 min increased significantly by $16.9 \pm 11.6\%$ ($P = 0.002$ $d = 1.56$), and 10 min increased significantly by $17.1 \pm 6.3\%$ ($P = 0.001$, $d = 1.44$) during the training phase. The calculated relative CP increased significantly by $16.8 \pm 6.2\%$ ($P = 0.007$, $d = 1.20$) (**Figures 4A–D**). Relative CP showed a high positive correlation with relative $MLSS_P$ ($r = 0.86$, $P < 0.001$), relative $MLSS_C$ ($r = 0.88$, $P < 0.001$), and relative VO_{2max} ($r = 0.85$, $P < 0.001$). Relative CP and dLa/dt_{max} showed a negative correlation of $r = -0.61$ ($P < 0.02$).

Training Data

Total mean training time was 366 ± 41 h leading to a pyramidal TID (zone 1: 63 ± 16%, zone 2: 28 ± 13%, zone 3: 9 ± 5%) (**Figure 5** top) and approximately ∼15.3 h of training per week using the classical 3-zone model. Total mean training time without power output below 50% $MLSS_P$ (power specific 3-zone model) was 261 ± 47 h and reflected a THR TID (zone 1: 48 ± 13%, zone 2: 39 ± 10%, zone 3: 13 ± 4%) (**Figure 5** bottom). Overall-ANOVA revealed that the percentage of training in the HVT-zone was significantly higher ($P = 0.003$), the percentage of training in the THR-zone ($P = 0.02$) and HIT-zone ($P = 0.008$) was significantly lower in the classical 3-zone model compared to

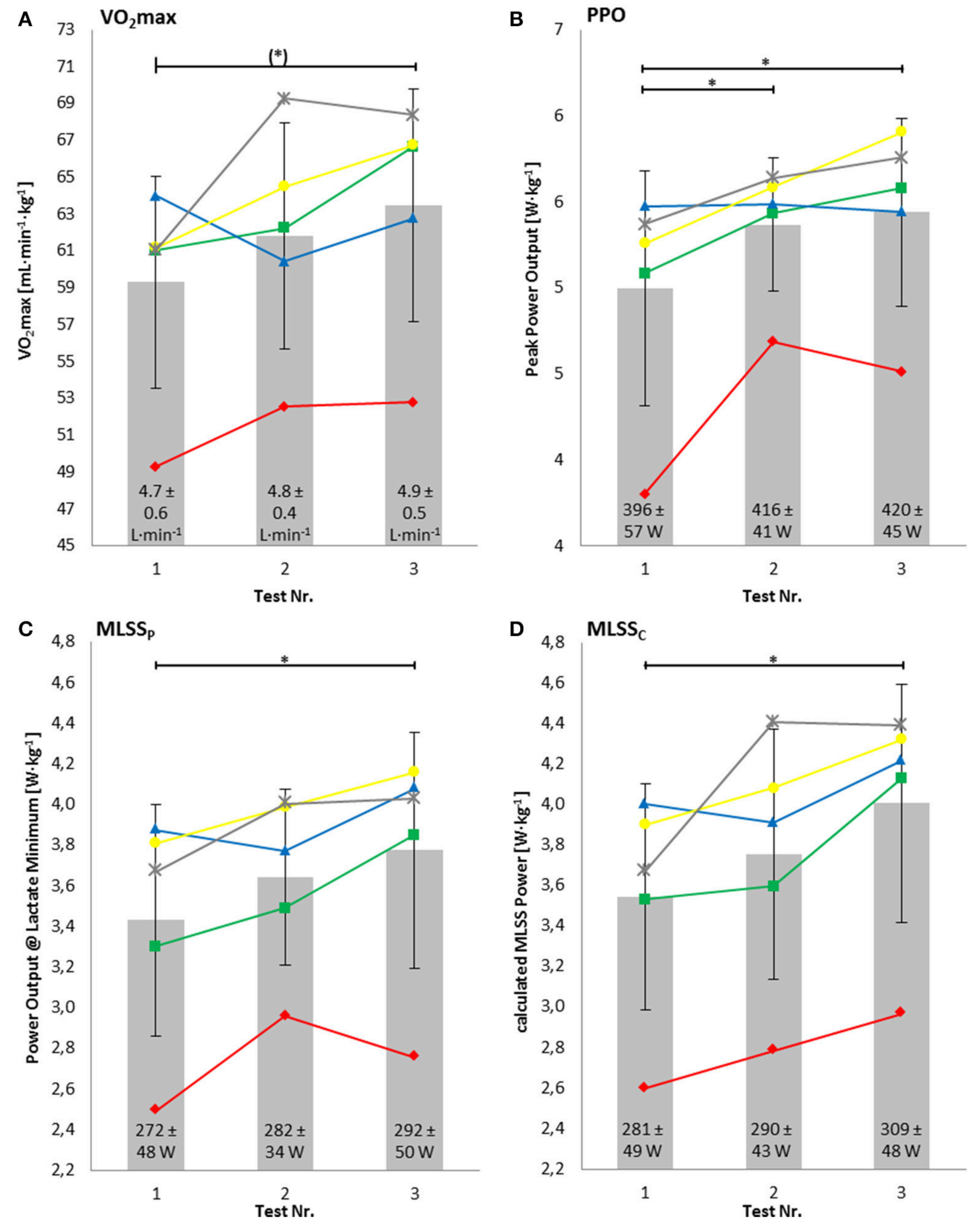

FIGURE 2 | Relative maximal oxygen uptake (VO_{2max}) (A), relative peak power output (PPO) **(B)**, relative power output at lactate minimum ($MLSS_P$) **(C)**, and relative power output at calculated maximal lactate steady state ($MLSS_C$) **(D)**. Numbers within the bars represent the absolute values. *Significant difference; (*) values nearly reached statistical significance ($P = 0.06$).

the power specific 3-zone model during each of the 6 months of training.

Race Data

Individual race data (time, distance, altitude difference, average relative power output, average power output, average power output in percent of $MLSS_P$, average power output in percent of LT1, and average cadence) are shown in **Table 3**.

DISCUSSION

The aim of the present study was to analyze the TID for a Race Across America Team with two different approaches and to examine the corresponding development of physiological parameters as well as the actual performance over the course of the preparation for the race, where the team finished in second place. Over the training period of 6 months, the five athletes reduced their body fat significantly. Moderate increases

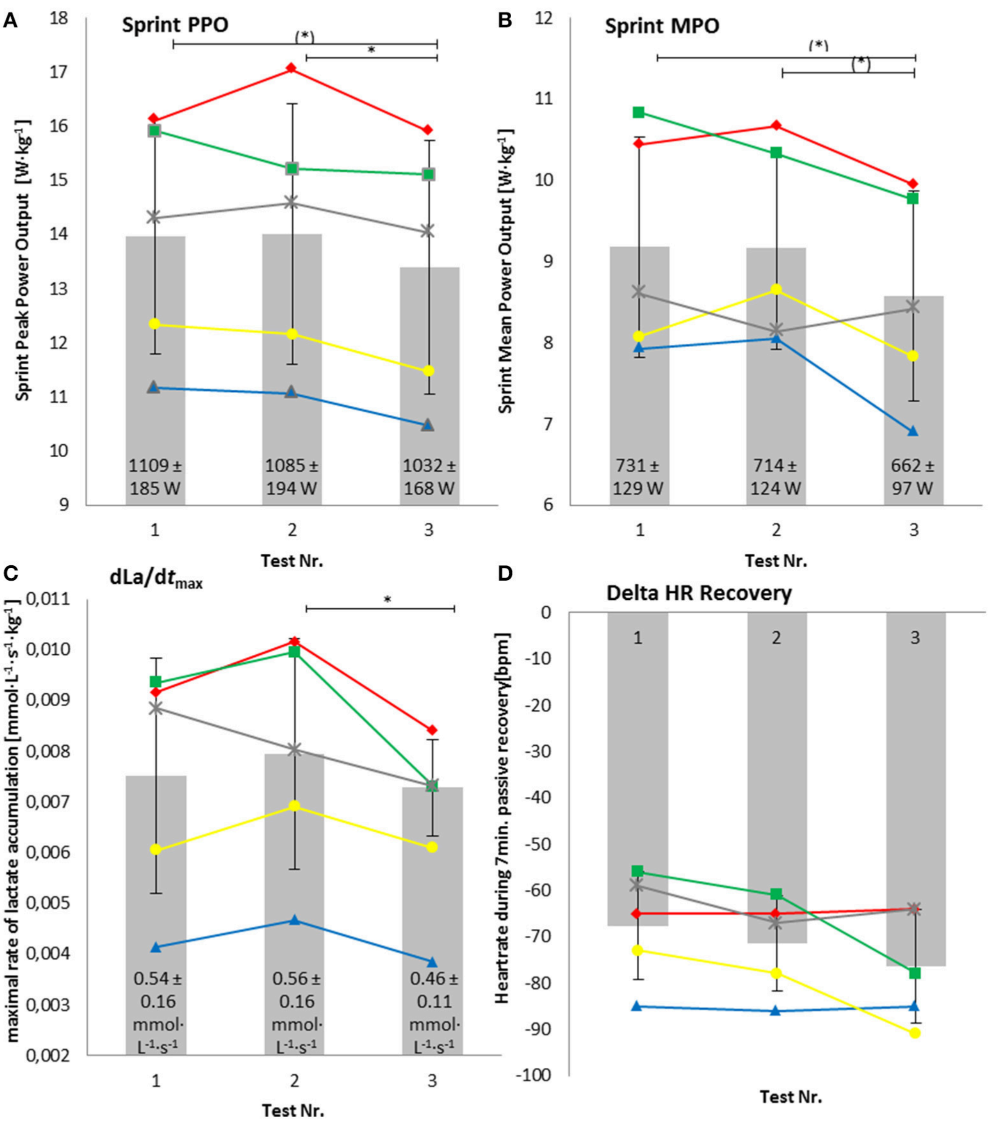

FIGURE 3 | Relative peak power output in the sprint test (Sprint PPO) (A), relative mean power output in the sprint test (Sprint MPO) **(B)**, maximal lactate production rate (dLa/dt$_{max}$) **(C)**, and drop in heart rate after 7 min of passive recovery after maximal exhaustion (Delta HR Recovery) **(D)**. Numbers within the bars represent the absolute values. *Significant difference; (*) values nearly reached statistical significance ($P = 0.06$).

were shown in relative VO_{2max} and moderate decreases in dLa/dt$_{max}$. Power output at MLSS ($MLSS_P$ and $MLSS_C$) increased significantly together with performance as indicated by the calculated CP. As an additional indication of increased fitness levels, moderate effects were shown by the drop in heart rate within 7 min of passive recovery. The TID of the established 3-zone model reflected a PYR TID (zone 1: 63 ± 16%, zone2: 28 ± 13% and zone 3: 9 ± 4%). Deleting training time with power output below 50% of $MLSS_P$, resulted in a THR TID (zone 1: 48 ± 13%, zone 2: 39 ± 10%, zone 3: 13 ± 4%).

The different results of our two approaches concerning TID, underline that the inherent variability in power output during training raises several challenges when attempting to evaluate the exact nature of a given training session. Different strategies on how to analyze power data have been suggested (Allen and Coggan, 2010). Allen and Coggan (2010) proposed using an exponentially weighted averaging process to represent the data. We decided to use an alternative approach, eliminating time with zero or very low power output, based on the assumption that a certain threshold intensity needs to be reached to result in an effective training stimulus (Davies and Knibbs, 1971). According to Meyer et al. (1999) and Wolpern et al. (2015), we decided to use a lactate threshold orientated lower fix point for the determination of zone 1 and set the minimum power output necessary to elicit a stimulus for training adaptation to 50% of $MLSS_P$. Applying the classic 3-zone model in the present study, weekly training time is similar to a report of athletes participating in a RAAM qualifying race (Knechtle et al., 2012b).

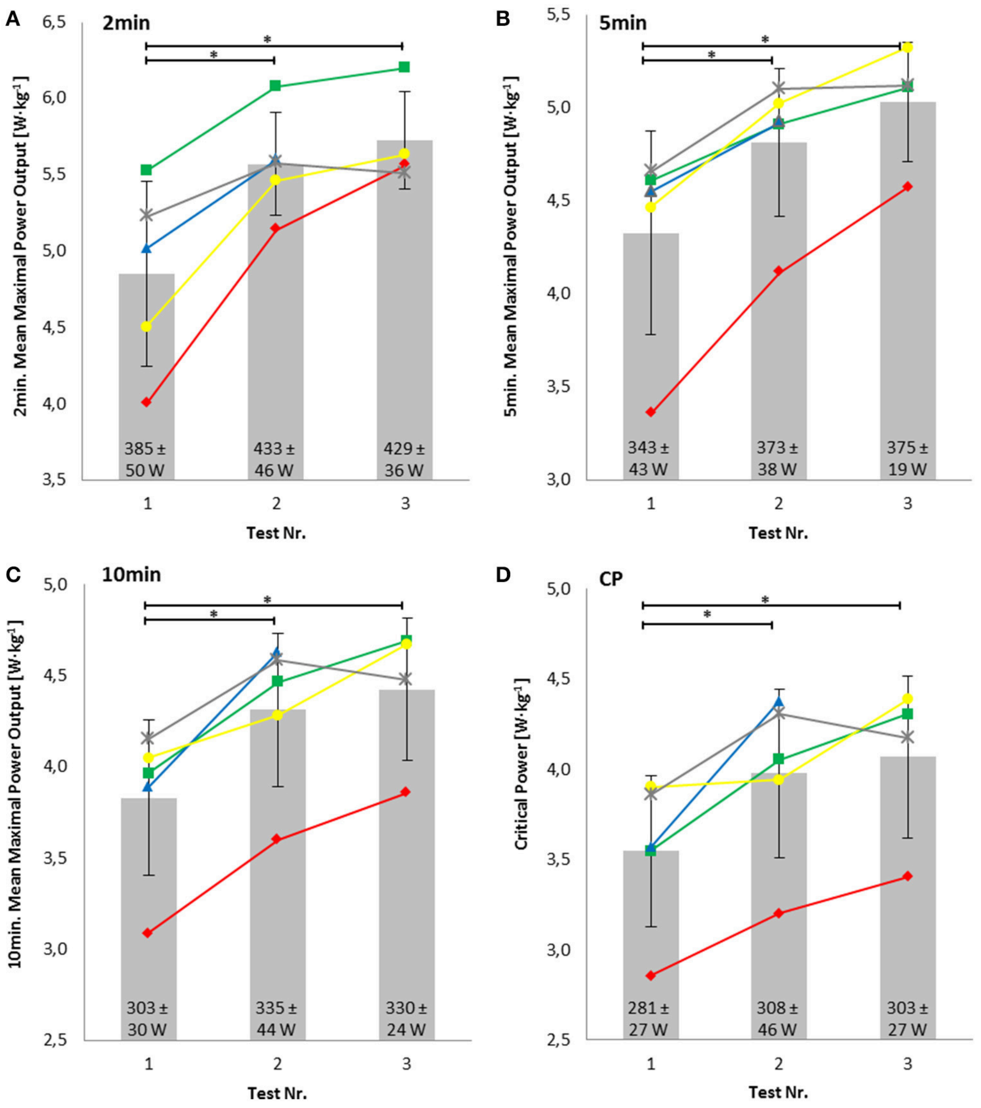

FIGURE 4 | Relative mean maximal power output in the field tests over 2 min (A), 5 min **(B)** and 10 min **(C)** and the calculated relative critical power (CP) **(D)**. Numbers within the bars represent the absolute values. *Significant difference.

However, when using the power specific 3-zone model in our study, total training time is reduced by 104 ± 7 h per athlete, leading to a THR TID. Our athletes, therefore, performed a lot of training between LT1 and MLSS, which was shown to be a rather ineffective training intensity when the goals are to gain performance improvements and physiological adaptations (Esteve-Lanao et al., 2007; Yu et al., 2012; Stöggl and Sperlich, 2014).

Luciá et al. (2000) and Aagaard et al. (2011) studied professional cyclists and young top-level national cyclists for periods of seven (PYR TID) and four (unknown TID) months, respectively. Despite higher weekly training volumes compared to our athletes, they could not show significant changes in VO_{2max}. The authors concluded that the very high fitness level of their athletes prevented further improvements for this parameter. In contrast, 7 months of a PYR TID with slightly more training per week (+ ∼1 h) than above-mentioned studies, led to significant improvements in relative VO_{2max} of 10% in fourteen male young top-level national road cyclists (Zapico et al., 2007). In any way, lactate values for a given sub-maximal workload during a ramp test decreased after the 7 months of training, suggesting an increased reliance on oxidative metabolism (Luciá et al., 2000), MMP over 5 min increased significantly (Aagaard et al., 2011) and MLSS increased by 15% (Zapico et al., 2007), which is in line with our results. Since our cyclists were not top levels athletes, it is very unlikely that they reached a ceiling of improvement for VO_{2max}. Nonetheless, there were only small increases in relative VO_{2max}, which can mainly be attributed to reductions in body weight. It can be speculated that the amount of HIT/SIT, which was shown to be most effective in improving

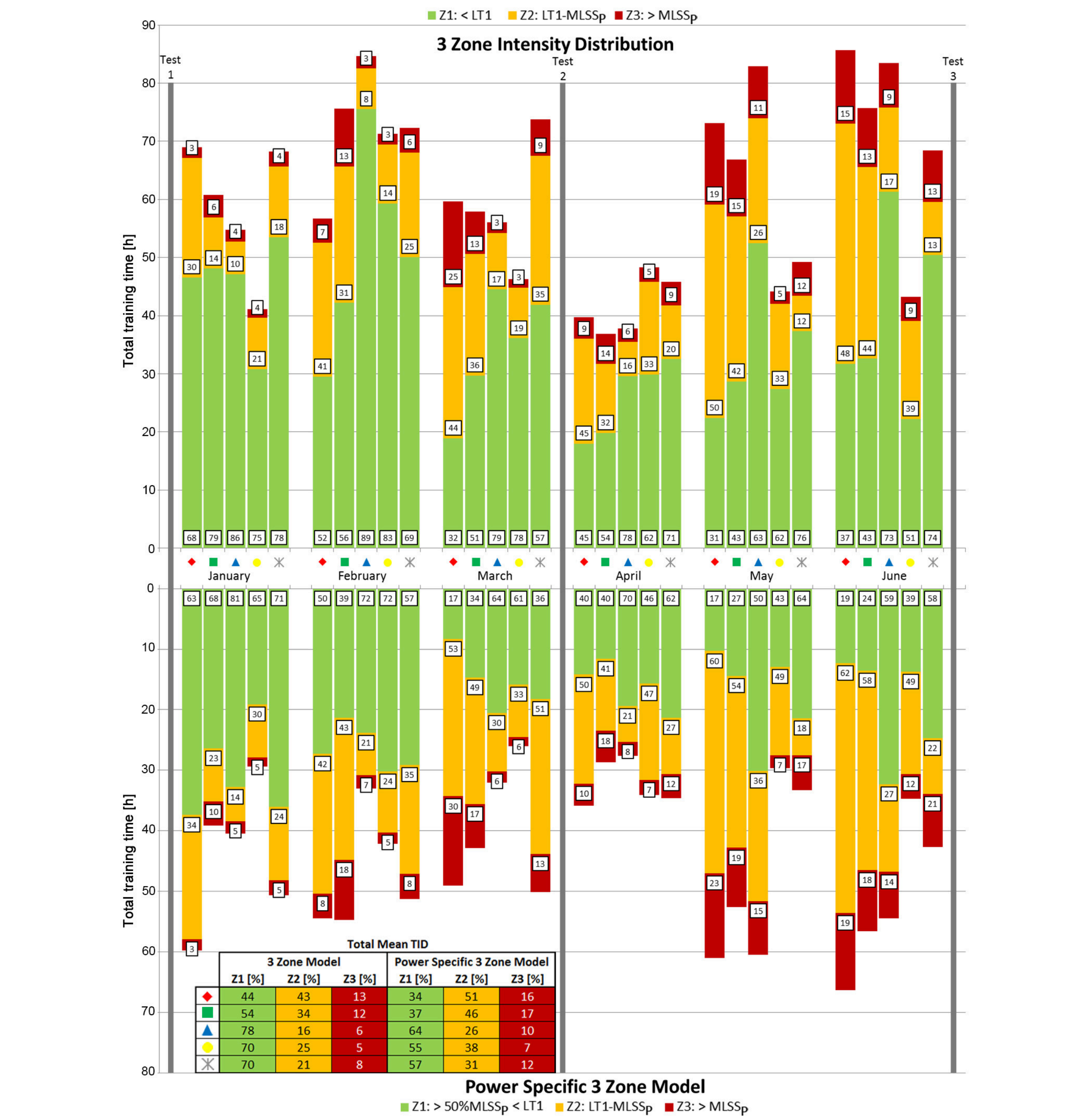

FIGURE 5 | Training intensity distribution according to the 3 zone model (top) and the power specific 3 zone model (bottom) over the time course of 6 months. Numbers in boxes represent the percentage of total training time spent in each zone per month for each athlete. Vertical arrows assign performance tests. Symbols represent each individual athlete. The included table shows the TID of each athlete for the whole preparation period.

VO_{2max} (McKenna et al., 1997; Dawson et al., 1998; MacDougall et al., 1998; Breil et al., 2010; Gibala et al., 2012; Etxebarria et al., 2014; Milanović et al., 2015) was too low in the present study to increase VO_{2max} substantially, especially in the context of the limited regular training volume. However, the decrease in dLa/dt_{max} and the corresponding increase in MLSSp power output underline the importance to document changes in these parameters, besides VO_{2max}, in order to gain more insight into physiological changes, leading to performance improvements (e.g., the rise in CP).

Additionally, Zapico et al. (2007) observed parallel to an increase in PPO, a significant reduction in maximal heart rate

TABLE 3 | Competition data of each individual racer (colored symbols) during the Race Across America.

Athlete	Time [hh:mm]	Distance [km]	Altitude difference [m]	Average power [W·kg^{-1}]	Average power [W]	Power [% MLSS]	Power [% LT1]	Average cadence [rpm]
◆ (red)	29:55	890	7411	2.3	186	85	141	78
■ (green)	34:41	1081	9566	2.6	199	69	100	88
● (yellow)	45:16	1628	9528	2.8	214	69	91	88
✱ (grey)	37:08	1184	9100	2.7	187	69	92	90

during a ramp test after 7 months of training, which is in contrast to our athletes. It has to be taken into account, however, that the subjects in our study were ~25 years older and ~11 kg heavier, which might partly explain the overall lower values, especially in VO_{2max}, as well as the smaller improvements. The TIDs, although being PYR in both studies, differ in so far, that our subjects trained fewer hours in total (−105 h) and to a less extent in zone 1 (−9.5%), and more in zone 2 (+6.5%). It can be speculated that the higher amount of THR training might be one reason for the lower gains in the physiological variables of the present study (Laursen, 2010). This assumption is supported by the study of Neal et al. (2011), who monitored 10 triathletes over a 6 month training period with a mean training volume of 203 ± 71 h. Similar to our athletes, these triathletes performed a PYR TID with a high amount of THR training, resulting in no changes in power output at lactate turn point. The lower effectiveness of a THR TID is further supported by another study of Neal et al. (2013), which resulted in greater improvements in 40-km time trial and LT1 and lactate turn point in a group of cyclists training POL when compared to a THR TID.

The LMT and the calculation of the MLSS ($MLSS_C$) using VO_{2max} and dLa/dt_{max} were shown to be valid to determine MLSS (Knöpfli-Lenzin and Boutellier, 2011; Hauser et al., 2014a). The fact that both independent methods to determine the power output at MLSS showed a high correlation underlines that the increases in MLSS were accurately determined. Additionally, the present study is the first to document changes in MLSS over the course of a training period for cyclists using these two approaches. Only four previous studies investigated the effects of training on the lactate minimum. Carter et al. (1999) showed that the LMT is not sensitive to identify longitudinal effects of endurance training in sports students over 6 weeks, despite significant improvements in VO_{2max}. Similar to our results, three other studies found significant increases in the LM intensity, investigating elite and youth soccer players (da Silva et al., 2007; Miranda et al., 2013) and youth swimmers (Campos et al., 2014), supporting that the LMT can be performed to identify longitudinal training effects. Again, this is further supported by the high correlation of the two methods we used to determine MLSS.

According to Hauser et al. (2014b), the MLSS is mainly influenced by VO_{2max} and dLa/dt_{max}. While VO_{2max} and its influence on endurance performance has been focused on in most endurance studies (Coyle et al., 1988; Schumacher and Mueller, 2002; Støren et al., 2012), dLa/dt_{max} has been neglected and appears to be an underestimated parameter in terms of the origin and interpretation of MLSS (Mader and Heck, 1986).

The present study is the first to describe changes in the dLa/dt_{max} over a long training period, and also its correlation with performance (CP, MLSS, MPO). Based on the model of Mader and Heck (1986) only both together—the moderate increase in VO_{2max} (7.1%) and to a larger proportion the decrease in dLa/dt_{max}(16.3%)—can explain the increase in performance (MLSS, CP) as measured in the present study. In accordance with the decrease in dLa/dt_{max} is the loss of anaerobic power, also reflected by the decrease in PPO and MPO within the sprint test. However, we found no significant changes in the strength assessments for five athletes. This is partly in line with the findings of Aagaard et al. (2011), where cyclists' maximal isometric strength, tested via leg press, also remained unchanged, after performing only endurance training over a period of 4 months.

The analysis of our race data showed, that three athletes used similar relative power outputs in relation to their $MLSS_P$ and LT1. The race intensity of our athletes is in agreement with the data of Laursen et al. (1999), who described a mean intensity slightly below the ventilatory threshold of a 4 person RAAM team. A solo racer during the RAAM performed at slightly lower intensities (77% of LT1) (Schumacher et al., 2011). The weakest subject in our study performed more intense with regards to % of $MLSS_P$ and % of LT1 during the race, which might be due to the lower distance and altitude differences that he had to cover compared to the other riders. Another explanation might be that this athlete had the highest relative amounts of training time in zone 2 and 3, compared to the stronger riders. It has been reported before, that the cycling speed during the training units was significantly and negatively related to race time (Knechtle et al., 2011, 2012b). Nevertheless, differences in race performances in ultra-endurance events can also result from various other influencing factors like race tactics, weather conditions, motivation (Lahart et al., 2013), sleep deprivation (Knechtle et al., 2012a), nutrition (Stewart and Stewart, 2007; Hulton et al., 2010; Bescós et al., 2012; Lahart et al., 2013; Paulin et al., 2015) and so on, which are not taken into account in this publication.

CONCLUSION

The present study shows a THR orientated TID and only moderate (Cohen, 1988) increases in physiological parameters. The resulting TID, however, may largely depend on the kind of analysis of power data. The amount of training below 50% of MLSS in our amateur athletes is remarkably high (104 h (∼28% of total training time)). Researchers, coaches, and athletes, either analyzing TID retrospectively or planning training in advance, should pay close attention to the different ways of interpreting training data, to gain realistic insights in TID and the corresponding improvements in performance and physiological parameters. In matters of physiological parameters determined during training periods, power output at LT1 seems to be a good estimate of long-term endurance performance. Future studies, therefore, should consider measuring dLa/dt_{max} and MLSS in addition to VO_{2max} and performance.

AUTHOR CONTRIBUTIONS

CM: performed tests and statistics, acquired data, and wrote the paper. JM: wrote paper. WK: acquired data. PW: performed tests and statistics, acquired data, and wrote the paper.

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