# How do the effects of an 8-week intervention influence subsequent performance development in cross-country skiers?

*Original investigation*

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## Abstract

**Purpose**: To investigate how the effects of increased low- vs. high-intensity endurance training in an 8-week intervention influenced the subsequent development of performance and physiological indices in cross-country skiers. **Methods**: Forty-four (32 men and 14 women) junior cross-country skiers were randomly assigned into a low- (LITG, n=20) or high-intensity training group (HITG, n=24) for an 8-week intervention followed by 5 weeks of standardized training with similar intensity distribution, and thereafter 14 weeks of self-chosen training. Performance and physiological indices in running and roller-ski skating were determined pre-intervention, after the intervention (POST-1), and after the standardized training period (POST-2). Roller-ski skating was also tested after the period of self-chosen training. **Results**: No between-group changes from pre-intervention to POST-2 were found in peak speed when incremental running and roller-ski skating (P=0.83 and 0.51), although performance in both modes was improved in LITG (2.4% [4.6%] and 3.3% [3.3%], P<0.05) and in roller-ski skating for HITG (2.6% [3.1%], P<0.01). While improvements in $VO_{2max}$ running and $VO_{2peak}$ roller-ski skating were greater in HITG than LITG from pre-intervention to POST-1, no between-group differences were found from pre-intervention to POST-2 (P=0.50 and 0.46), although $VO_{2peak}$ roller-ski-skating significantly improved within HITG (5.7% [7.0%], P<0.01). No changes neither within nor between groups were found after the period of self-chosen training. **Conclusions**: Differences in adaptations elicited by a short-term intervention focusing on low- vs. high-intensity endurance training had little or no effects on the subsequent development of performance or physiological indices following a period of standardized training in cross-country skiers.



**Keywords:** endurance training, training intensity, training volume, periodization, XC skiing.

## Introduction

Manipulation of training intensity and volume are key factors for optimizing adaptive responses from endurance training.[1-4] Retrospective analyses have demonstrated that successful elite endurance athletes prioritize high volumes of low-intensity training (LIT) combined with low-to-moderate amounts of moderate- (MIT) and high-intensity training (HIT) in the general preparation period. Thereafter, the specific and/or competition period is often characterized by reduced volume and more intensified training.[1-3]

Performance improvements in the competition period following intensification is supported by several short-term experimental studies showing superior training adaptations while adopting a more polarized intensity distribution with augmented HIT stimulus.[5-7] Specifically, it has been argued that intensification is needed to further elicit physiological adaptations (e.g. maximal oxygen uptake [$VO_{2max}$)] in already well-trained to elite endurance athletes.[7-10] However, the majority of previous training studies are limited by employing methods for matching of training load that are not valid (i.e. iso-energetic method) and/or by using short intervention periods (4-12 weeks). Consequently, we do not know how the effect of short-term training interventions would influence the subsequent training periods or if their effectiveness would be maintained over longer time spans. In this context, intensified training in the transition period of well-trained cyclists led to more positive performance-development in the subsequent training period.[11] However, the long-term effects of short-term training interventions during the preparation period in endurance athletes is currently unexplored.

In a recent study,[12] progression of training load by increased HIT during an 8-week intervention period elicited 3–4% greater $VO_{2max}$ adaptations than progressing the load by increased volume LIT, although the performance-development did not statistically differ between the groups of cross-country skiers. Both training regimes were matched for overall load, and these findings indicate an intensity-dependent diversity in the development of performance-determining physiological factors. However, the extent to which these differences in training adaptations influence the subsequent development of performance and physiological indices is yet unknown.

Therefore, the main purpose of this follow-up study was to investigate how the effects of increased LIT vs. HIT in an 8-week intervention period influenced the subsequent development of performance and physiological indices in well-trained cross-country skiers. This was achieved by comparing the further development in performance and physiological adaptations following 5 weeks of standardized training with similar intensity distribution across groups, and thereafter 14 weeks of self-chosen training.

## Methods

This study extends upon the findings of a recent training intervention conducted among well-trained junior cross-country skiers in their preparation period.[12] Following an 8-week pre-intervention period (July-August), the athletes were randomly assigned into either a group with increased load of LIT (LITG) or HIT (HITG) for an 8-week intervention (September-October) simulating a *general preparation period*. Performance and physiological adaptations to this period in a larger study sample is reported elsewhere.[12] Thereafter, the athletes (LITG, n=24; 8 women and HITG, n=20; 6 women) performed 5 weeks of standardized training (November) simulating a *specific preparation period* with similar intensity distribution, followed by 14 weeks of self-chosen training in the *competition period* (December-March). Laboratory performance and physiological indices in running and roller-ski skating were determined before (PRE), after the 8-week intervention (POST-1), and after the 5-week standardized training period (POST-2). Roller-ski skating was also tested in the last week of the 14-week period of self-chosen training (POST-3). The complete study protocol is displayed in Figure 1.

**Figure 1**

**Participants**

Forty-four (32 men and 14 women) cross-country skiers (8 biathletes) participated in the study. Participant characteristics pre-intervention are presented in Table 1. The Regional Committee for Medical and Health Research Ethics waived the requirement for ethical approval for this study. Therefore, the ethics of the study is done according to the institutional requirements and approval for data security and handling obtained from the Norwegian Centre for Research Data. All athletes were fully informed with the nature of the study and its experimental risks before providing a written informed consent of their participation. The athletes were explicitly informed that they could withdraw from the study at any point in time without providing a reason for doing so. Several athletes (n=19) were <18 years, and therefore, each of their parents was asked to provide parental consent for their child's participation. Three athletes in LITG dropped out of the 5-week training period due to sickness. In addition, five athletes in LITG (sickness=3, injury=2) and four athletes in HITG (sickness= 3, injury=1) were not able to perform the test in the 14-week period of self-chosen training. Overall, 32 athletes performed POST-3 (LITG, n=16; 6 women; HITG, n=16; 5 women) All athletes in the final analyses met the criteria of 85% compliance with the prescribed training both in the intervention and subsequent 5-week training period.

**Table 1**

**Design**

After the preceding 8-week intervention,[12] both groups performed a 5-week standardized training period while following similar training regimes. The goal of this period was to simulate a *specific preparation period* where we used similar training intensity distribution across groups. This included reduced HIT duration and increased HIT intensity, more speed training, and increased amounts of sessions performed in competition-specific terrain. Training plans were programmed with three different mesocycle load structures (high, moderate and low), where the coaches individually selected and adjusted the load while aiming to optimize adaptive responses for each athlete. Accordingly, the 5-week period with similar intensity distribution led to intensification both in the amount of HIT sessions and by increasing the intensity of HIT sessions for LITG, whereas HITG reduced volume HIT but intensified the stimulus. Training characteristics for both the 8-week intervention and subsequent 5-week period are presented in Table 2. Typical MIT sessions were e.g. 5x8-min with 2-min recovery in between or 45-min continuous work, whereas typical HIT sessions were e.g. 5x4-min with 2.5-min recovery or 7x3-min with 2-min recovery periods. Laboratory performance and physiological indices in running and roller-ski skating were determined within the first 5 days after both periods. The 14-week follow-up period consisted of self-chosen training and competitions. While the athletes' training in this period was not standardized, the same coaches programmed individual training plans and employed similar training methods (training form and intensity) as in the two preceding periods, although more on-snow ski-specific training was performed. However, the competition schedule was highly limited by the COVID-19 pandemic and therefore, the competition period consisted mostly of training and simulated competitions. The roller-ski skating test was performed within the last week of the 14-week period.

**Table 2**

**Training monitoring**

All athletes recorded their own training using an online training diary developed by the Norwegian Top Sport Centre (*Olympiatoppen*) by applying the *modified session-goal approach.*[13] All training was systematized by training form (endurance, strength and speed), intensity (LIT, MIT and HIT) and mode (specific [roller-skiing/skiing] and non-specific [running and cycling]). For MIT- and HIT-sessions performed as intervals, time in the intensity zone of the session was registered from the beginning of the first interval to the end of the last interval, including recovery periods. Laboratory tests and competitions were also quantified as HIT. Moreover, strength and speed training were registered from the start to the finish of that separate part (e.g. strength, speed, plyometrics) during the session, including recovery periods. Endurance training load using the training impulse (TRIMP) method was calculated by multiplying the duration in the three intensity zones with a weighting factor (i.e. LIT, MIT, and HIT was given a score of 1, 2, and 3, respectively). Total TRIMP was then obtained by adding the different intensity-zone scores. [14, 15] Heart rate (HR) monitoring and [$La^-$] measurements were regularly used to ensure intensity control during both the intervention and 5-week training period.

**Test protocols and measurements**

The training plans included standardized training loads (LIT sessions) over the last two days prior to testing. All athletes were instructed to follow their own preparation procedures before reporting to the laboratory on two separate occasions (running and roller-ski skating) with a minimum of 24 h in between.

*Performance and physiological indices*

Preceding both tests, a 10-min warm-up in running was performed (60-72% of maximal HR [$HR_{max}$]). The running test consisted of one 5-min submaximal workload followed by an incremental test to determine $VO_{2max}$ and performance measured as peak speed ($V_{peak}$).[16] The roller-ski skating test consisted of two 5-min submaximal workloads followed by an incremental test to determine peak oxygen uptake ($VO_{2peak}$) and $V_{peak}$. [16] Roller-ski skating was performed using the G3 (V2) sub-technique. Detailed protocols for both tests can be found elsewhere [12] and in appendix 1.

Running was performed on a 2.5x0.7-m motor-driven treadmill, and roller-ski skating on a 3.5x2.5-m treadmill (RL 2500 and RL 3500E, Rodby, Vänge, Sweden). Respiratory recordings were collected between the third and fourth minute of each submaximal workload. HR was defined as the average over the last 30 s. Respiratory variables were measured using open-circuit indirect calorimetry with mixing chamber (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany) and HR measured by use of a Garmin Forerunner 935 (Garmin Ltd., Olathe, KS, USA). Rating of perceived exertion (RPE) using the 6-20-point Borg scale and [$La^-$] were determined directly after completing each submaximal workload. [$La^-$] were measured using the stationary Biosen C-Line lactate analyser (Biosen, EKF Industrial Electronics, Magdeburg, Germany). Gross efficiency was measured for submaximal roller-ski skating and defined as the ratio of work rate and metabolic rate.[17] All athletes used the same pair of skating roller-skis (IDT Sports, Lena, Norway) to reduce variations in rolling resistance. The roller-skis were pre-warmed through 20-min of roller-skiing before each test session and rolling friction force measured with a towing test as previously described by Sandbakk et al. [17] For the incremental tests, respiratory variables and HR were measured continuously, and $VO_{2max}$ in running $VO_{2peak}$ in roller-ski skating defined as the highest 1-min average. $HR_{max}$ was defined as the highest 5-sec HR measurement during each test, whereas RPE was determined directly after, and [$La^-$] approximately 1 min after completing the tests.

**Statistical analysis**

All data are reported as mean (SD). Training characteristics between-groups were compared using an independent samples t-test. To test for differences between groups, a General linear model (GLM) analysis of covariance (ANCOVA) was used, with the percentage change between test time-points as the dependent variable, and pre-intervention values as a covariate to adjust for possible between-group differences pre-intervention. Effect size (ES) was calculated to test for practical significance according to Cohen's d both within- and between-groups (interpreted as following: 0.0-0.24 trivial, 0.25-0.49 small, 0.5-1.0 moderate, >1.0 large).[18] Adopted from previous literature,[19, 20] individual response magnitudes were calculated and defined in three different categories: nonresponse, <0% change; moderate response, 0% to 5% change and large response, >5% change. For all comparisons, statistical significance was set at an alpha level of P<0.05 and P=0.05-0.1 indicated trends. All data analyses were carried out using SPSS 27.0 (SPSS Inc, Chicago, IL, United States).

**Results**

Performance and physiological adaptations to the 8-week intervention are previously described in detail. [12] In brief, there were no significant differences in performance adaptations between increased load of LIT vs. HIT, but increased HIT elicited superior $VO_{2max}$ adaptations compared to increased LIT.

In the subsequent 5-week period, there was no significant difference between groups in △body mass from POST-1 to POST-2 (P=0.10) with no changes within groups (LITG, -0.2% [1.1%], P=0.42; ES=0.01) and HITG, 0.6% [1.5%], p=0.12; ES=0.01). However, there was a between-group difference in △body mass from PRE- to POST-2 (P=0.04, Table 3), with an increase in HITG (2.4% [2.4%], p<0.01; ES=0.20) and a corresponding non-change in LITG (0.5% [2.0%], P=0.31; ES=0.01).

**Table 3**

*Performance adaptations*

Performance indices in running and roller-ski skating are shown in Table 3-4 and Figure 2. There was no significant difference between-groups in △$V_{peak}$ running from POST-1 to POST-2 (P=0.12), with no significant within-group changes (1.0% [3.0%], P=0.15; ES=0.14 and -0.5% [2.5%], P=0.32; ES=0.10, in LITG and HITG, respectively). Similarly, no between-group difference in △$V_{peak}$ running from PRE- to POST-2 was found (P=0.83) although a significant improvement was shown in LITG (2.4% [4.6%], P=0.04; ES=0.29) and a corresponding trend in HITG (1.8% [3.9%], P=0.09; ES=0.19).

There was no significant difference between groups in △$V_{peak}$ roller-ski skating from POST-1 to POST-2 (P=0.12), although an improvement was found in LITG (1.8% [2.6%], P=0.01; ES=0.22) but not HITG (0.4% [2.5%], P=0.49; ES=0.00). From PRE- to POST-2, no significant between-group difference in △$V_{peak}$ roller-ski skating was found (P=0.51). However, within-group improvements were shown in both LITG (3.3% [3.3%], P<0.01; ES=0.41) and HITG (2.6% [3.1%], P<0.01; ES=0.29). These findings were further strengthened by the frequency distribution of individual response magnitudes in performance adaptations (Figure 3).

**Table 4**
**Figure 2**
**Figure 3**

*Physiological adaptations*

Physiological indices in running and roller-ski skating are shown in Table 3-4 and Figure 2. There was a trend towards significant difference between groups in $\triangle VO_{2max}$ running from POST-1 to POST-2 (P=0.06), with an improvement in LITG (2.1% [3.0%], P<0.01; ES=0.14) and a corresponding non-change in HITG (0.1% [3.4%], P=0.98; ES=0.00). Therefore, $\triangle VO_{2max}$ running was not significantly different between groups from PRE- to POST-2 (P=0.50), although a trend was found in HITG (3.0% [6.0%], P=0.06; ES=0.15) but not in LITG (1.4% [5.0%], P=0.32; ES=0.08).

There was no between-group difference in $\triangle VO_{2peak}$ roller-ski skating from POST-1 to POST-2 (P=0.33) but an improvement found in LITG (3.7% [5.5%], P=0.02; ES=0.22) and a trend in HITG (1.8% [4.3%], P=0.07; ES=0.12). Consequently, $VO_{2peak}$ roller-ski skating did not differ between groups from PRE- to POST-2 (P=0.46) but were significantly improved in HITG (5.7% [7.0%], P<0.01; ES=0.33) and showed a trend in LITG (3.8% [6.9%], P=0.06; ES=0.22). These findings coincided with the frequency distribution of individual response magnitudes in $VO_{2max}$ adaptations (Figure 3).

More positive submaximal adaptations were found in LITG from POST-1 to POST-2 and therefore, similar adaptations within both groups were shown comparing PRE- to POST-2 (see Table 3-4 for all details). Moreover, gross efficiency in roller-ski skating was improved within both groups from POST-1 to POST-2 and when comparing PRE- to POST-2, no differences between-groups in △gross efficiency were found (Table 4).

*14-week follow-up period*

$V_{peak}$ and $VO_{2peak}$ in roller-ski skating did not change neither within nor between groups from POST-2 to POST-3 (Figure 4). Similar findings were observed for body mass, as well as for physiological and perceptual responses at both submaximal workloads during roller-ski skating.

**Figure 4**

**Discussion**

The purpose of this follow-up study was to investigate how the effects of increased low- vs. high-intensity endurance training in an 8-week intervention period influenced the subsequent development of performance and physiological indices in well-trained cross-country skiers. The main finding was that differences in training adaptations elicited by the short-term intervention had little or no effects on the subsequent development of performance or physiological indices following 5 weeks of standardized training with similar intensity distribution across groups, and thereafter14 weeks of self-chosen training.

*Performance adaptations*

In a recent study,[12] we showed no statistical differences in performance progression (i.e. $V_{peak}$ and TTE) by increased load of LIT vs. HIT during an 8-week intervention in the preparation period among cross-country skiers, although individual response magnitudes indicated more positive performance effects by increased HIT. The present follow-up study investigated the subsequent performance development of this short-term training intervention. Here, the tendencies for better performance adaptations in HITG during the intervention was outbalanced by within-group performance improvements in LITG during the subsequent training period. Accordingly, intensification during these 5 weeks had positive performance effects in LITG, although it remains unknown whether these improvements were caused by adopting more HIT *per see* or by the change from prioritizing high-volume LIT to more intensified training (i.e.

*traditional periodization model*), which might have elicited complementary adaptive responses.[2, 3] In comparison, performance indices did not change in HITG during the subsequent 5-week training period, which are likely explained by already maximized intensification-effects during the intervention. These findings agree with a previous study by Sylta et al.[19] demonstrating that most training adaptations elicited by intensification occurred already within the first 4 weeks of a 12-week intervention investigating the effects of different HIT ordering and its adaptation time course in well-trained cyclists.

During the 14-weeks of self-chosen training in the subsequent competition period, we found no further changes in any performance or physiological indices neither within- nor between groups. These findings agree with a previous study in elite male XC skiers,[21] where most improvements in performance indices occurred during the preparation period, with only minor changes in the competition period. Our findings are, however, in contrast to a study with comparable design conducted among well-trained cyclists, demonstrating positive effects of implementing HIT during an 8-week intervention in the transition period on performance indices 16 weeks into the subsequent preparation period.[11] However, these conflicting findings are likely explained by differences between implementing more HIT in the transition period where the overall training load is reduced vs. in the preparation period with higher training loads.

*Physiological adaptations*

Although increased HIT load elicited 3–4% greater improvements in $VO_{2max}$ in running and $VO_{2peak}$ in roller-ski skating compared to increased LIT load during the 8-week intervention, [12] no statistical differences in any physiological adaptations were found between groups after the following 5 weeks with standardized training or after 14 weeks of self-chosen training. These findings are coincided by similar individual response magnitudes, and we additionally found no differences in any submaximal adaptations (e.g. $\%VO_{2max/peak,}$ [La$^-$], respiratory exchange ratio [RER]) between groups. Hence, the subsequent 5-week period with similar intensity distribution across groups, and thereby intensification for LITG, outbalanced the superior $VO_{2max}$ adaptations achieved by HITG during the preceding 8-week intervention period.

Interestingly, a considerably lower HIT stimulus during the 5-week training period elicited somewhat similar $VO_{2peak}$ adaptations when roller-ski skating in LITG compared to the effects achieved by HITG during the more intensive 8-week intervention. These findings may suggest an "*ceiling-effect*", with an upper limit for how much HIT that is needed to maximize $VO_{2max}$ adaptations in already well-trained endurance athletes. This hypothesis is partly supported by Billat et al. [22] who found that intensification beyond 1 HIT and 1 MIT session per week gave no further improvements but instead increased markers of negative training stress. However, in our recent study, ~1 HIT and ~1 MIT session per week in LITG during the intervention only maintained baseline $VO_{2peak}$ values in roller-ski skating, whereas $VO_{2max}$ in running was slightly reduced.[12] Therefore, the present data suggests that although ~1 HIT and ~1 MIT session per week might be sufficient to maintain $VO_{2max}$ values, ~2-3 weekly HIT sessions are likely needed to maximize $VO_{2max}$ and other physiological adaptations in well-trained endurance athletes. However, the volume and intensity within these intensity domains can vary extensively between sessions and adaptive responses from HIT and/or MIT are also dependent on optimal interaction between intensity and total work duration.[23, 24] The intensification-effects on $VO_{2max}$ in the present study also occurred within a relatively short time frame which agrees with the findings by Sylta et al. [19] Lastly, it should be noted that $VO_{2max}$ adaptations were only trivial to small within both groups (ES, 0.1-0.3), which are somewhat lower than those reported in comparable training studies.[19, 25] The reason for this is not known but are most likely related to differences in athletes training status. Accordingly, future work should further investigate the optimal manipulation of training volume and intensity to maximize $VO_{2max}$ and other performance-determining variables over longer time scales in endurance athletes. It should also be emphasized that individual variations in training responses were found, indicating differences in how athletes respond to different training intensities and periodization models. Accordingly, individualized training intensity and periodization are likely needed to optimize long-term performance development in cross-country skiing.

**Limitations**

The present study includes some limitations. First, training data during the 14-week follow-up period was missing. Within- and between-group differences in training might therefore have influenced our findings on long-term effects of the intervention, which were also performed on a reduced sample of athletes. However, the same coaching team programmed individual training plans and employed similar training methods during this period as in the intervention and standardized training period. Second, our current design only included laboratory performance indices and not real-world performance measures that requires attention in future studies. It should also be noted that the HR monitoring used were based on incremental testing and $\%HR_{max}$, which might elicit different responses during training sessions and thus have influenced the training intensity prescribed.[26] Third, the present sample of athletes included both sexes which might have influenced the observed training adaptations. However, no significant effect of sex was found in any performance or physiological adaptations and our group comparisons are therefore likely valid for both sexes. Adopting information on menstrual cycle phase and the use of hormonal contraceptives among female participants to the experimental design would also have further strengthened the study.

**Practical applications**

The present data provides novel insights on how the effects of a typical short-term training intervention in the preparation period influence the subsequent development of performance and physiological adaptations in cross-country skiers. This is important information for sport scientists and practitioners working with endurance athletes. Based on these findings, we argue that positive training effects found in previous and future short-term intervention studies should be interpreted with caution until their effectiveness for long-term development has been shown. It should also be noted that positive effects of different short-term training interventions might in part be explained by changes in the training stimulus *per se* and could therefore be seen as *training periodization*. Accordingly, there is an uttermost need for future training studies investigating how manipulations of training intensity and volume are translated into performance and physiological benefits over longer time scales in endurance athletes. While interpretating the findings of the study, it should be emphasized that some of the findings might differ in other endurance sports with different competitive demands than in cross-country skiing.

**Conclusions**

The present study shows that differences in adaptations elicited by a short-term training intervention focusing on increased low vs. high intensity training had little or no effects on the subsequent development of performance and physiological indices following 5 weeks of standardized training with similar intensity distribution across groups. Furthermore, there were no differences between the two training models following 14 weeks of self-chosen training in the subsequent competition period.

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**Table 1.** Participants characteristics pre-intervention.

| **Variables** | **Men (n = 32)** | **Women (n = 12)** | **Total (n = 44)** |
|---|---|---|---|
| Age (y) | 18 (1) | 17 (0) | 18 (1) |
| Body height (cm) | 181.0 (5.9) | 167.0 (3.0) | 177.4 (8.0) |
| Body mass (kg) | 72.0 (6.7) | 60.7 (4.1) | 69.1 (7.9) |
| Body mass index ($kg \cdot m^{-2}$) | 22.0 (1.6) | 21.8 (1.9) | 21.9 (1.7) |
| $VO_{2max}$ ($L \cdot min^{-1}$) running | 5.03 (0.55) | 3.42 (0.29) | 4.61 (0.86) |
| $VO_{2max}$ ($mL \cdot min^{-1} \cdot kg^{-1}$) runing | 69.8 (4.6) | 56.2 (2.8) | 66.3 (7.3) |
| $VO_{2peak}$ ($L \cdot min^{-1}$) roller-ski skating | 4.76 (0.54) | 3.28 (0.27) | 4.33 (0.82) |
| $VO_{2peak}$ ($mL \cdot min^{-1} \cdot kg^{-1}$) roller-ski skating | 66.3 (5.1) | 53.8 (3.4) | 62.7 (7.3) |
| Annual training volume ($h \cdot y^{-1}$) | 525 (93) | 490 (99) | 515 (97) |

$VO_{2max}$, maximal oxygen uptake; $VO_{2peak}$, peak oxygen uptake. The values are presented as mean (SD).

**Table 2.** Training characteristics during an 8-week intervention period and subsequent 5-week standardized training period in 41 well-trained cross-country skiers, randomized into two different training models.

| | 8-week intervention period | | 5-week subsequent period | |
|---|---|---|---|---|
| | LITG (n = 21) | HITG (n = 20) | LITG (n = 21) | HITG (n = 20) |
| **Training forms** | | | | |
| Training volume (h/wk) | 14.0 (1.3) | 11.4 (1.4)* | 13.0 (2.3) | 12.7 (3.1) |
| Sessions (sessions/wk) | 8.5 (0.6) | 8.4 (0.9) | 8.7 (1.0) | 8.3 (2.0) |
| Sickness/injury (days) | 2.0 (2.9) | 1.7 (2.7) | 1.0 (2.0) | 0.4 (1.3) |
| **Training forms** | | | | |
| Endurance (h/wk) | 12.3 (1.1) | 10.1 (1.2)* | 11.3 (1.8) | 11.0 (3.1) |
| Strength (h/wk) | 1.2 (0.2) | 1.0 (0.3) | 1.4 (0.5) | 1.4 (0.5) |
| Speed (h/wk) | 0.5 (0.3) | 0.4 (0.2) | 0.3 (0.2) | 0.3 (0.2) |
| **Training mode** | | | | |
| Specific (h/wk) | 6.9 (1.1) | 5.3 (1.2)* | 6.4 (1.1) | 6.1 (1.8) |
| Non-specific (h/wk) | 5.4 (1.1) | 4.8 (1.3) | 4.6 (1.0) | 4.8 (1.4) |
| Specific/non-specific (%) | 55/45 | 53/47 | 58/42 | 56/44 |
| **Endurance training volume** | | | | |
| Compliance (%TRIMP) | 99.6 (10.0) | 100.0 (7.4) | 97.2 (8.0) | 96.9 (9.8) |
| Load (TRIMP/wk) | 784 (78) | 780 (80) | 780 (124) | 783 (131) |
| LIT (h/wk) | 11.3 (1.0) | 8.4 (1.0)* | 9.8 (1.6) | 9.5 (2.5) |
| MIT (h/wk) | 0.5 (0.1) | 0.6 (0.2) | 0.3 (0.2) | 0.4 (0.2) |
| HIT (h/wk) | 0.5 (0.1) | 1.1 (0.1)* | 0.9 (0.1) | 0.8 (0.2) |
| LIT/MIT/HIT (%) | 92/4/4 | 85/4/11 | 89/3/8 | 89/4/7 |
| **Endurance training sessions** | | | | |
| LIT (sessions/wk) | 5.7 (0.5) | 4.6 (0.76)* | 5.3 (0.6) | 5.0 (1.2) |
| LIT ≥2.5 h (sessions/wk) | 1.3 (0.2) | 0.3 (0.2)* | 0.7 (0.3) | 0.7 (0.4) |
| MIT (sessions/wk) | 0.6 (0.1) | 0.5 (0.1) | 0.5 (0.2) | 0.5 (0.3) |
| HIT (sessions/wk) | 0.9 (0.1) | 2.2 (0.2)* | 1.5 (0.2) | 1.4 (0.4) |
| LIT/MIT/HIT (%) | 79/8/12 | 65/7/28 | 73/7/20 | 73/7/20 |

LITG, low-intensity training group; HITG, high-intensity training group; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training. Compliance is calculated as percent of total TRIMP in relation to total TRIMP prescribed. *Significantly different from LITG (#p<0.05). The values are presented as mean (SD).

**Table 3.** Performance and physiological indices in running pre-intervention (PRE), following an 8-week intervention period (POST-1) and subsequent 5-week standardized training period (POST-2) in 39 well-trained cross-country skiers, randomized into two different training models.

| | LITG (n = 19) | | | HITG (n = 20) | | | LIGT vs. HITG |
|---|---|---|---|---|---|---|---|
| | PRE | POST-1 | POST-2 | PRE | POST-1 | POST-2 | ES |
| Body mass (kg) | 70.7 (7.5) | 71.3 (8.0) | 71.1 (7.9) | 67.6 (7.9) | 68.8 (7.7) | 69.2 (7.7)*# | 0.16 |
| **Submaximal running (7/8-km·h$^{-1}$)** | | | | | | | |
| $VO_2$ (L·min$^{-1}$) | 3.28 (0.47) | 3.19 (0.46) | 3.26 (0.50) | 3.13 (0.43) | 3.16 ± 0.44 | 3.21(0.44)*# | 0.16 |
| $VO_2$ in % $VO_{2max}$ | 70.9 (6.2) | 70.7 (4.4) | 69.4 (5.4) | 69.7 (5.5) | 68.3 ± 4.6 | 69.7 (5.9) | 0.27 |
| RER | 0.91 (0.04) | 0.92 (0.03) | 0.91 (0.04) | 0.92 (0.05) | 0.90 ± 0.03 | 0.92 (0.04) | 0.22 |
| HR (beats·min$^{-1}$) | 166 (12) | 164 (11) | 164 (9) | 165 (10) | 160 ± 8* | 163 (10) | 0.05 |
| HR in %$HR_{max}$ | 82.8 (4.7) | 81.7 (4.6) | 82.1 (3.9) | 82.5 (4.0) | 80.1 ± 4.0 | 81.3 (4.3)* | 0.06 |
| Borg (6-20) | 12.6 (1.4) | 12.2 (1.5) | 12.1 (1.4)* | 12.8 (1.4) | 12.2 ± 1.1 | 12.8 (0.9) | 0.35 |
| [La$^-$] (mmol·L$^{-1}$) | 2.10 (0.85) | 1.91 (0.62) | 1.92 (0.57)* | 2.27 (0.90) | 2.02 ± 0.74 | 2.19 (0.82) | 0.17 |
| **Time to exhaustion running** | | | | | | | |
| $VO_{2max}$ (L·min$^{-1}$) | 4.70 (0.91) | 4.65 (0.83) | 4.75 (0.87) | 4.54 (0.80) | 4.64 ± 0.71# | 4.64 (0.70) | 0.07 |
| $VO_{2max}$ (mL·min$^{-1}$·kg$^{-1}$) | 65.9 (7.5) | 64.9 (6.1) | 66.2 (7.1) | 66.7 (7.1) | 67.4 ± 6.2# | 67.1 (6.2) | 0.02 |
| RER | 1.12 (0.03) | 1.15 (0.04) | 1.12 (0.03) | 1.14 (0.05) | 1.14 ± 0.04 | 1.15 (0.05) | 0.25 |
| $HR_{max}$ (beats·min$^{-1}$) | 199 (6) | 198 (6.2) | 198 (6) | 198 (9) | 197 ± 7 | 200 (8) | 0.07 |
| [La$^-$] (mmol·L$^{-1}$) | 10.82 (1.48) | 11.49 (1.96) | 11.60 (1.61) | 11.48 (1.78) | 11.92 ± 1.88 | 11.51 (2.26) | 0.45 |
| TTE (s) | 351 (61) | 362 (55) | 371 (59)* | 359 (55) | 381 ± 45* | 374 (35) | 0.10 |
| $V_{peak}$ (km·h$^{-1}$) | 14.5 (1.4) | 14.7 (1.3) | 14.9 (1.3)* | 1 4.8 (1.2) | 15.1 ± 1.1* | 15.0 (0.9) | 0.08 |

LITG, low-intensity training group; HITG, high-intensity training group; ES, effect size of change from PRE- to POST-2 calculated according to Cohen's d; $VO_2$, oxygen uptake; $VO_{2max}$, maximal oxygen uptake; HR, heart rate; $HR_{max}$, maximal heart rate; [La$^-$], blood lactate; RER, respiratory exchange ratio; TTE, time to exhaustion; $V_{peak}$, peak velocity. *Significant different from PRE (*$p< 0.05$). #Significant different from change in LITG (#$p<0.05$). The values are presented as mean (SD).

**Table 4.** Performance and physiological indices in roller-ski skating using the G3 (V2) sub-technique pre-intervention (PRE), following an 8-week intervention period (POST-1) and subsequent 5-week standardized training period (POST-2) in 39 well-trained cross-country skiers, randomized into two different training models.

| | LITG (n = 20) | | | HITG (n = 19) | | | LIGT vs. HITG |
|---|---|---|---|---|---|---|---|
| | PRE | POST-1 | POST-2 | PRE | POST-1 | POST-2 | ES |
| **Submaximal roller-ski skating (10/12-km·h$^{-1}$)** | | | | | | | |
| $VO_2$ (L·min$^{-1}$) | 3.14 (0.53) | 3.07 (0.50)* | 3.09 (0.50) | 3.04 (0.43) | 3.02 (0.39) | 3.07 (0.41) | 0.17 |
| $VO_2$ in % $VO_{2peak}$ | 72.3 (5.2) | 70.7 (4.4)* | 68.9 (5.7)* | 71.7 (6.1) | 68.9 (4.8)* | 68.7 (5.3)* | 0.09 |
| RER | 0.93 (0.04) | 0.91 (0.03) | 0.91 (0.03)* | 0.96 (0.05) | 0.94 (0.03)* | 0.93 (0.03)* | 0.33 |
| HR (beats·min$^{-1}$) | 173 (10) | 173 (10) | 172 (9) | 170 (10) | 167 (9)*# | 66 (11)* | 0.30 |
| HR in %$HR_{max}$ | 86.2 (4.5) | 86.2 (3.7) | 85.8 (3.6) | 85.7 (3.8) | 84.2 (3.3)*# | 83.8 (4.6)* | 0.32 |
| Borg (6-20) | 11.1 (2.0) | 11.4 (1.8) | 11.6 (1.0) | 12.0 (1.2) | 11.8 (1.7) | 11.8 (1.4) | 0.38 |
| [$La^-$] (mmol·L$^{-1}$) | 2.69 (0.95) | 2.73 (0.79) | 2.43 (0.70) | 3.08 (1.24) | 2.84 (0.79) | 2.74 (1.06)* | 0.18 |
| GE (%) | 13.7 (0.7) | 14.1 (0.8) | 14.2 (0.7)* | 13.9 (0.8) | 14.3 (0.6)* | 14.5 (0.6)* | 0.10 |
| **Submaximal roller-ski skating (12/14-km·h$^{-1}$)** | | | | | | | |
| $VO_2$ (L·min$^{-1}$) | 3.52 (0.56) | 3.46 (0.52) | 3.48 (0.53) | 3.42 (0.48) | 3.41 (0.44) | 3.48 (0.47)# | 0.16 |
| $VO_2$ in % $VO_{2peak}$ | 81.1 (5.7) | 79.8 (4.7) | 77.6 (5.6)* | 80.9 (6.8) | 77.8 (4.9) | 78.1 (6.5)* | 0.10 |
| RER | 0.96 (0.04) | 0.95 (0.03) | 0.94 (0.03)* | 0.97 (0.03) | 0.96 (0.04)* | 0.95 (0.04)* | 0.28 |
| HR (beats·min$^{-1}$) | 184 (9) | 183 (8) | 182 (9) | 180 (11) | 178 (9)* | 178 (10)* | 0.11 |
| HR in %$HR_{max}$ | 91.6 (3.6) | 91.2 (3.2) | 90.9 (3.1) | 90.9 (3.7) | 89.8 (2.9) | 89.6 (4.0)* | 0.16 |
| Borg (6-20) | 14.4 (1.4) | 13.9 (1.4) | 14.1 (0.8) | 14.5 (1.2) | 14.0 (1.1)* | 14.2 (1.4) | 0.00 |
| [$La^-$] (mmol·L$^{-1}$) | 4.08 (1.43) | 4.04 (1.19) | 3.67 (1.33)* | 4.32 (2.06) | 4.21 (1.28) | 4.19 (1.95)* | 0.27 |
| GE (%) | 14.3 (0.6) | 14.6 (0.7)* | 14.8 (0.6)* | 14.4 (0.7) | 14.7 (0.6)* | 14.8 (0.8)* | 0.19 |
| **Time to exhaustion roller-ski skating** | | | | | | | |
| $VO_{2peak}$ (L·min$^{-1}$) | 4.39 (0.90) | 4.38 (0.85) | 4.53 (0.88) | 4.27 (0.73) | 4.41 (0.68)# | 4.50 (0.74)* | 0.10 |
| $VO_{2peak}$ (mL·min$^{-1}$·kg$^{-1}$) | 62.1 (8.5) | 62.0 (6.7) | 63.2 (7.1) | 63.3 (6.8) | 64.3 (6.0) | 65.3 (7.2)* | 0.12 |
| RER | 1.11 (0.05) | 1.10 (0.04) | 1.09 (0.03) | 1.11 (0.04) | 1.11 (0.04) | 1.10 (0.05) | 0.22 |
| $HR_{peak}$ (beats·min$^{-1}$) | 198 (7) | 98 (6) | 198 (6) | 196 (8) | 196 (7) | 196 (7) | 0.14 |
| [$La^-$] (mmol·L$^{-1}$) | 10.75 (1.74) | 10.83 (1.85) | 11.31 (2.02) | 10.69 (1.59) | 10.89 (1.88) | 11.36 (1.88) | 0.06 |
| TTE (s) | 278 (57) | 295 (57)* | 320 (62)* | 290 (73) | 318 (60)* | 321 (75)* | 0.22 |
| $V_{peak}$ (km·h$^{-1}$) | 20.8 (1.7) | 21.1 (1.7)* | 21.5 (1.9)* | 21.3 (1.8) | 21.8 (1.7)* | 21.8 (1.9)* | 0.20 |

LITG, low-intensity training group; HITG, high-intensity training group; ES, effect size of change from PRE- to POST-2 calculated according to Cohens d; $VO_2$, oxygen uptake; $VO_{2peak}$, peak oxygen uptake; HR, heart rate; $HR_{peak}$, peak heart rate; [$La^-$], blood lactate; GE, gross efficiency; RER, respiratory exchange ratio; TTE, time to exhaustion; $V_{peak}$, peak velocity; *Significant different from PRE (*$p< 0.05$). #Significant different from change in LITG (#$p<0.05$). The values are presented as mean (SD).

**Figure captions**

**Figure 1.** Complete study protocol. An 8-week pre-intervention period, including familiarization, pre-testing and randomization followed by an 8-week intervention with either increased low- or high-intensity endurance training, and a subsequent 5-week standardized training period with similar intensity distribution.

**Figure 2.** **(A)** $\triangle V_{peak}$ running, **(B)** $\triangle VO_{2max}$ running, **(C)** $\triangle V_{peak}$ roller-ski skating and **(D)** $\triangle VO_{2peak}$ roller-ski skating from PRE- to POST-2 in LITG (grey line) and HITG (black line). *Significant change from PRE within LITG ($p<0.05$). †Significant change from PRE within HITG ($p<0.05$). #Significant difference in change between groups ($p<0.05$).

**Figure 3.** Frequency distribution of individual responses from PRE- to POST-2 summarized in three different categories: nonresponse (white), <0% change; moderate response (grey), 0–5% change; and large response (black) >5% change. **(A)** $\triangle V_{peak}$ running, **(B)** $\triangle VO_{2max}$ running **(C)** $\triangle V_{peak}$ roller-ski skating **(D)** $\triangle VO_{2peak}$ roller-ski skating.

**Figure 4.** **(A)** $\triangle V_{peak}$ roller-ski skating and **(B)** $\triangle VO_{2peak}$ roller-ski skating from PRE- to POST-3 in LITG (grey line) and HITG (black line). *Significant change from PRE within LITG ($p<0.05$). †Significant change from PRE within HITG ($p<0.05$). #Significant difference in change between groups ($p<0.05$).

**Figure 1.**

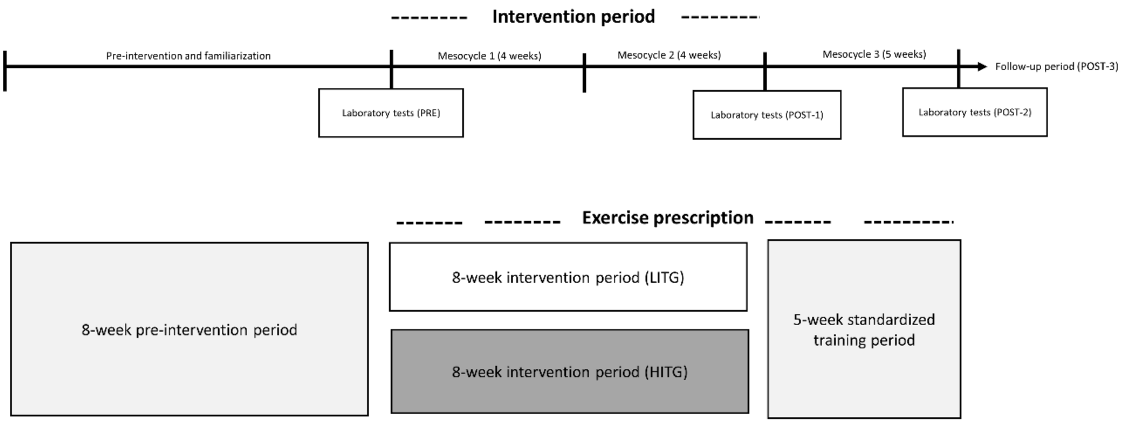



**Figure 2.**

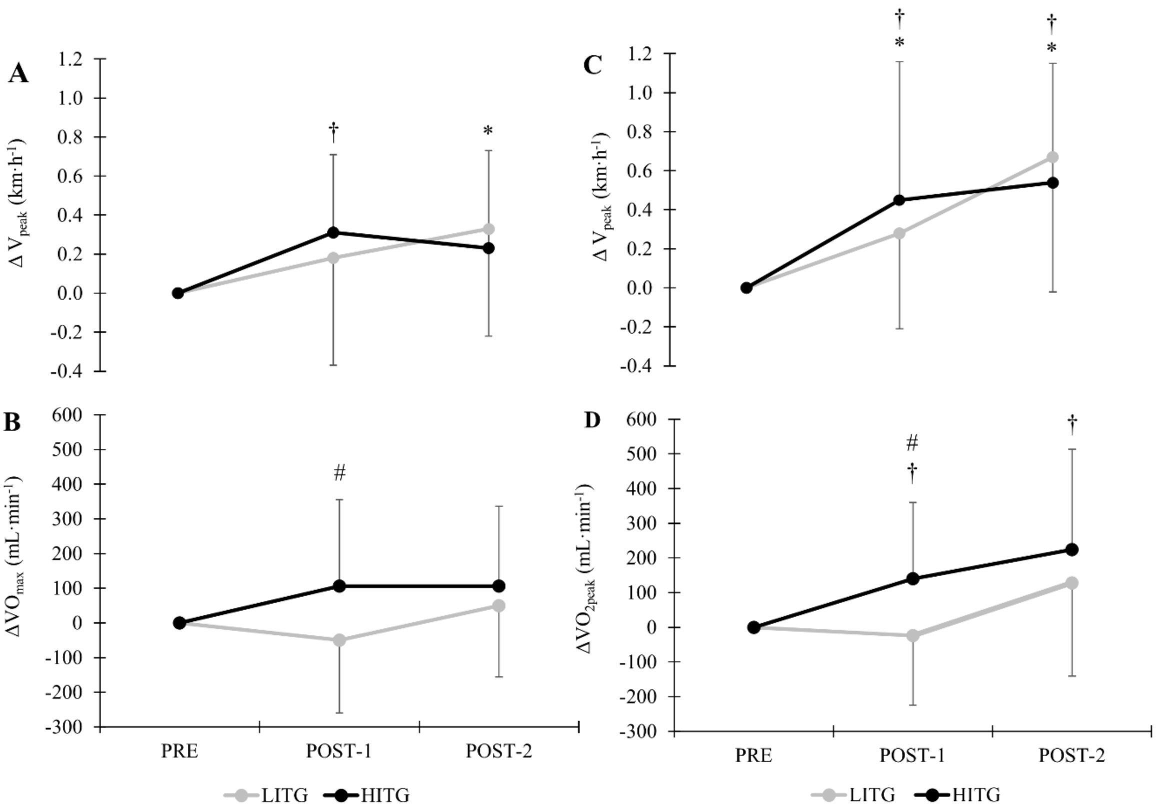
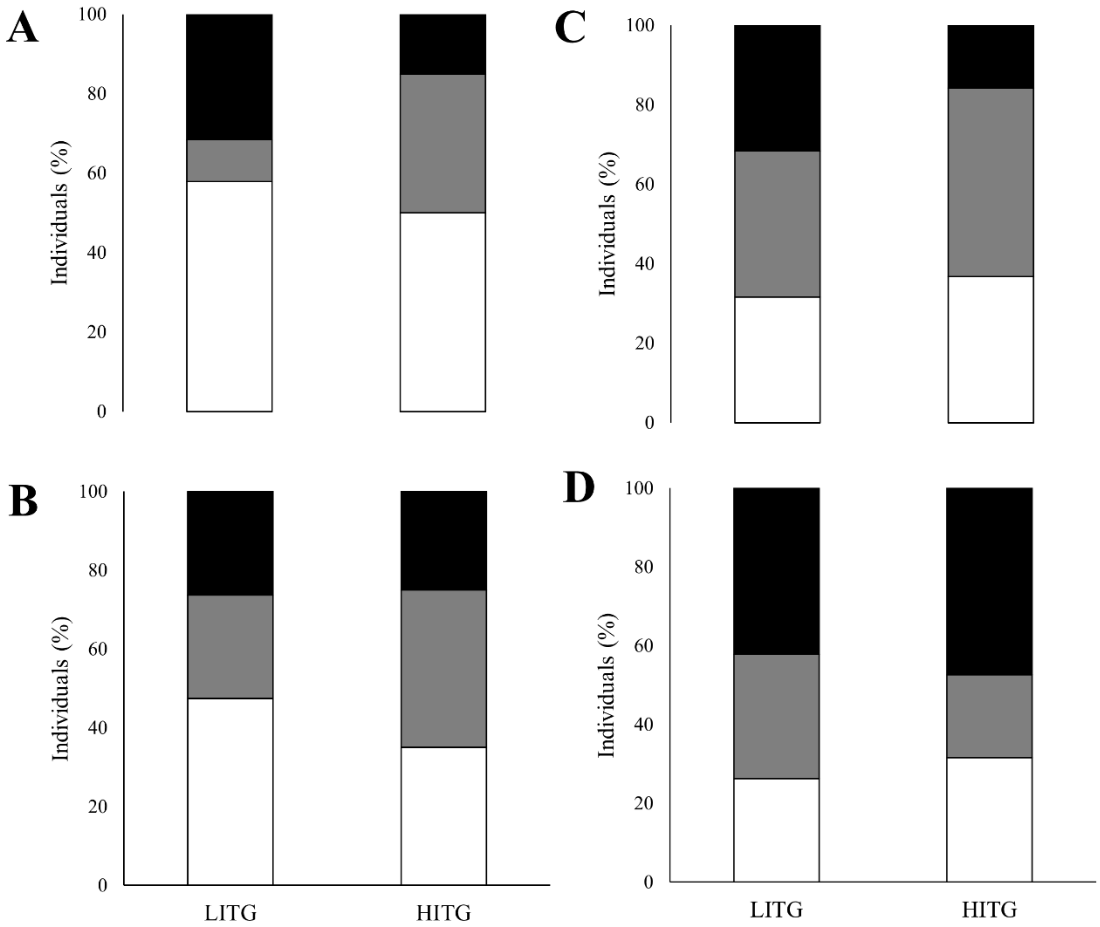
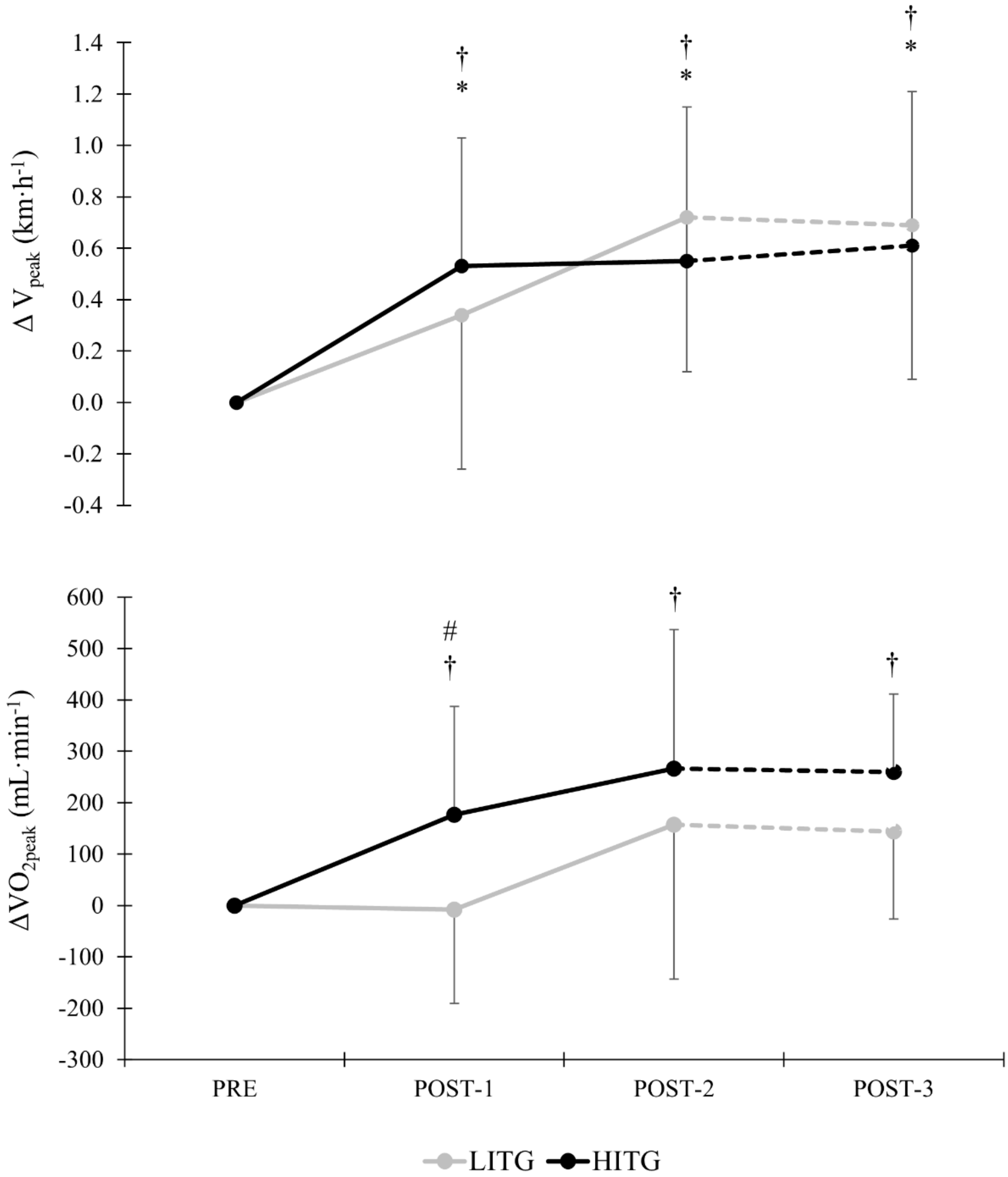


**Figure 3.**



615 **Figure 4.**

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