Effects of increased load of low- vs. high-intensity endurance training on performance and physiological adaptations in endurance athletes

Original investigation

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Abstract

Purpose: To compare the effects of increased load of low- vs. high-intensity endurance training on performance and physiological adaptations in well-trained endurance athletes.

Methods: Following an 8-week pre-intervention period, fifty-one (36 men and 15 women) junior cross-country skiers and biathletes were randomly allocated into a low-intensity (LIG, n=26) or high-intensity training group (HIG, n=25) for an 8-week intervention period, load-balanced using the overall training impulse (TRIMP)-score. Both groups performed an uphill running time-trial and were assessed for laboratory performance and physiological profiling in treadmill running and roller-ski skating pre- and post-intervention.

Results: Pre- to post-intervention changes in running time-trial did not differ between groups (p=0.44), with significant improvements in HIG (-2.3±3.2%, p=0.01) but not in LIG (-1.5±2.9%, p=0.20). There were no differences between groups in peak speed changes when incremental running and roller-ski skating to exhaustion (p=0.30 and p=0.20, respectively), with both modes being significantly improved in HIG (2.2±3.1% and 2.5±3.4%, both p<0.01) and in roller-ski skating for LIG (1.5±2.4%, p<0.01). There was a between-group difference in running VO_{2max} changes (p=0.04), tending to improve in HIG (3.0±6.4%, p=0.09) but not in LIG (-0.7±4.6%, p=0.25). Changes in roller-ski skating VO_{2peak} differed between groups (p=0.02), with significant improvements in HIG (3.6±5.4%, p=0.01) but not in LIG (-0.1±0.17%, p=0.62).

Conclusion: There were no significant difference in performance adaptations between increased load of low- vs. high-intensity training in well-trained endurance athletes although both methods improved performance. However, increased load of high-intensity training elicited better VO_{2max} adaptations compared to increased load of low-intensity training.

Keywords: biathlon, endurance performance, maximal oxygen uptake, training intensity distribution, training volume, XC skiing

Introduction

Endurance training involves the manipulation of training intensity, duration, frequency and mode, with the goal of maximizing physiological adaptations and performance.[1,2] Accordingly, the organization and optimization of endurance training, and in particular training volume and intensity distribution, is widely debated among both sports scientists and practitioners.[1-3] Most elite endurance athletes adopt a training model consisting of high volumes of low-intensity training (LIT) combined with low-to-moderate amounts of moderate- (MIT) and high-intensity training (HIT).[1-3] However, the exact volume and training intensity distribution depends on the demands of the given endurance sport, individual requirements, as well as the phase of the annual training cycle.[1,3,4]

Endurance athletes progress their overall training stimulus throughout the annual cycle, which might be achieved through increased load of LIT or by performing a larger load of MIT and/or HIT.[1] While LIT is seen as an important stimulus for inducing peripheral adaptations such as increased mitochondrial biogenesis and capillary density of the skeletal muscle,[5,6] central adaptations such as increased stroke volume of the heart, leading to improved maximal oxygen uptake (VO_{2max}), are regarded as more responsive to HIT.[5-7] However, LIT and HIT have many similarities (e.g., upregulating PGC-1α) and both intensities seem to elicit complex and integrated adaptations.[1,5]

To better understand how progression in endurance training load by different intensity distributions influence performance and physiological adaptations in endurance athletes, valid methods for the matching of training load is required. The majority of previous intervention studies where training load has been matched for total work or oxygen consumption (iso-energetic method) emphasizes the superiority of HIT for maximizing physiological adaptations.[7-9] However, such studies are not realistic from the perspective of how endurance athletes train and perceive stress,[3] since endurance athletes can perform far more work, both energetically and in terms of total work at a lower autonomic disturbance, with LIT compared to HIT.[10] Accordingly, progressing the overall training stimulus with increased load of LIT may be advantageous for optimizing adaptative responses at a tolerable level of stress, although most experimental evidence suggests superior adaptations while adopting a more polarized intensity distribution[11] with greater training intensification.[12]

Therefore, the present study compared the effects of increased load of LIT vs. HIT during an 8-week intervention period on performance and physiological adaptations in well-trained endurance athletes. This was done by matching the increase of LIT and HIT for overall load by the training impulse method (TRIMP), in which we hypothesized that more HIT would elicit superior VO_{2max} adaptations and thereby greater performance improvements compared to more LIT over 8 weeks.

Methods

Participants

Fifty-one (36 men and 15 women; Table 1) national-level junior cross-country skiers and biathletes volunteered to participate in the study. All athletes were students at a Norwegian high school with a specialized study program for cross-country skiing (n=41) and biathlon (n=10). The Regional Committee for Medical and Health Research Ethics waived the requirement for ethical approval for this study. Therefore, the ethics of the study are in accordance with the institutional requirements, and approval for data security and handling obtained from the

Norwegian Centre for Research Data (NSD). All athletes were fully informed of the nature of the study and its experimental risks before providing written consent. Several athletes (n=21) were <18 years, and therefore, the parents were asked to provide parental consent. Some athletes dropped out of the study (low-intensity training group [LIG]=2; high-intensity training group [HIG]=5) due to sickness (n=3), injury (n=2), or other reasons (n=2). In addition, two athletes from LIG were excluded from the final analyses due to lack of 85% compliance with the prescribed training.

Table 1 around here

Design

Following an 8-week pre-intervention period, the athletes were randomly allocated into either a group with increased load of LIT (LIG, n=26) or a group with increased load of HIT (HIG, n=25) for an 8-week intervention during their late preparation period (September–November). The training was balanced for overall load using a TRIMP score, and groups were matched for sport, age, sex, physiological indices, and pre-intervention training characteristics. Both groups performed an uphill running time-trial (TT) in the field and were assessed for laboratory performance and physiological profiling in treadmill running and roller-ski skating before (pre) and after (post) the intervention.

Methodology

Pre-intervention period

Prior to the intervention, all athletes followed an 8-week baseline period consisting of the same training guidelines. The athletes were instructed to focus on high-volume LIT interspersed with, on average, one weekly MIT and one weekly HIT session. In addition, 2–3 weekly strength or speed sessions were integrated into LIT sessions or performed as a single session. Based on this, individualized training programs were developed together with the athlete’s personal coaches to ensure optimal adjustments of load. The athletes were familiarized with the different test protocols before performing all pre-tests during the last week of the pre-intervention period.

Intervention period

Training plans during the 8-week intervention period were based on a theoretical framework developed by the researchers and adopted to each athlete in close collaboration with coaches. The groups increased their overall training load in the intervention period by adopting two different training regimes. LIG continued with the same focus as during the pre-intervention period, but with increased volume of LIT, whereas HIG changed towards increased frequency and volume of HIT with reduced volume of LIT. Weekly mesocycle load was designed with three different load structures (high, moderate, and low) for both groups, where the coaches, individually adjusted and optimized load for each athlete. Based on previous research [13,14] and pilot testing of selected athletes, the use of the training impulse (TRIMP) method was incorporated as the most valid method for the matching of training load between groups. Accordingly, all within-group mesocycle loads were balanced for overall load (TRIMP) between-groups. TRIMP was calculated by multiplying the duration in three intensity zones with a weighting factor (i.e., LIT, MIT, and HIT are given a score of 1, 2, and 3, respectively). Total TRIMP was then obtained by adding the different intensity zone scores. Distribution of MIT and HIT sessions per week together with weekly mesocycle loads for both groups are displayed in Figure 1. All athletes were instructed to maintain the same diet and training plans were designed to maintain similar volume of strength and speed training during the intervention period.

Figure 1 around here

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* (SG/TZ).[15] Training intensity distribution was recorded using a five-zone intensity scale but reported using a three-zone scale (LIT, MIT, and HIT), which better corresponds with relevant literature and underlying physiological mechanisms.[16] 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. 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. Training mode is reported as specific (classical and skating roller-skiing) and non-specific (running and cycling) endurance training. In addition, intensity control was achieved by regular use of heart rate (HR) monitoring and [La^-] measurements throughout the intervention period.

Test protocols and measurements

Training plans were designed to include standardized training load in the last two days prior to the first day of testing. The athletes were instructed to follow self-selected preparation procedures and not to consume any large meals or caffeinated beverages within the last 2 hours before the test. There were always >24 hours between all tests for each athlete. The TT in combination with laboratory tests were chosen to obtain a comprehensive understanding of performance both in practical and laboratory conditions, as well as the underlying physiological mechanisms.

Uphill running TT (test day 1)

Prior to the TT, athletes performed a ~30-min LIT self-selected warm-up procedure. Performance times were recorded using two synchronized watches and the Racesplitter timekeeping system (Makalu Logistics Inc, Fontana, USA). The TT was performed on asphalt with a total distance of 6.4 km (elevation: 270 m) and 4.5 km (elevation: 160 m) for men and women, respectively. Weather conditions were stable during each test day, being partly cloudy with low and stable wind, but differed in ambient temperature and humidity between pre and post (15 vs. 2 °C and 70 vs. 90%, respectively). Due to different reasons, six athletes in LIG and one athlete in HIG were not able to perform the TT at both pre and post. Hence, 35 athletes were included in the final TT analysis (LIG, 10 men and 5 women; HIG, 14 men and 5 women).

Laboratory treadmill running test (test day 2)

Following a 10-min individual running warm-up (60–72% of maximal HR [HR_{max}]), all athletes performed one 5-min submaximal stage running at 10.5% incline and at the same absolute speed (8 $km \cdot h^{-1}$ for men and 7 $km \cdot h^{-1}$ for women). After a 2-min recovery period, the athletes performed an incremental test to exhaustion in order to determine VO_{2max} and performance measured as peak treadmill speed ([V_{peak}] calculated according to Sandbakk et al .,[17]). The test was performed at 10.5% incline with a 1-$km \cdot h^{-1}$ increase in speed every minute until voluntary exhaustion. Starting speed was set to 9 $km \cdot h^{-1}$and 8 $km \cdot h^{-1}$ for men and women, respectively.

Laboratory treadmill roller-ski skating test (test day 3)

After a 10-min individual running warm-up (60–72% of HR_{max}) as on test day 2, the athletes completed two 5-min submaximal stages at 5% incline while treadmill roller-ski skating. The two stages were performed at the same absolute speed for men (12 and 14 $km \cdot h^{-1}$) and women (10 and 12 $km \cdot h^{-1}$), with 1-min recovery in between. Following a 5-min recovery period, peak oxygen uptake (VO_{2peak}) and performance measured as V_{peak} were determined.[17] The test was performed at 5% incline with a starting speed of 14 and 12 $km \cdot h^{-1}$ for men and women, respectively. The incline was kept constant, while the speed was subsequently increased by 2 $km \cdot h^{-1}$ every minute up to 20 $km \cdot h^{-1}$ for men and 18 $km \cdot h^{-1}$ for women, and thereafter by 1 $km \cdot h^{-1}$ until voluntary exhaustion. The athletes were instructed to use the skating G3 sub-technique during the entire test.

Treadmill running was performed on a 2.5 x 0.7-m motor-driven treadmill and treadmill roller-ski skating on a 3.5 x 2.5-m treadmill (RL 2500 and RL 3500E, Rodby, Vänge, Sweden). For all submaximal testing, respiratory recordings were collected between the third and fourth minute of each 5-min stage and HR 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 by a Garmin Forerunner 935 (Garmin Ltd., Olathe, KS, USA). Rate of perceived exertion (RPE) using the 6–20-point Borg scale and [La] were taken from the fingertip directly after completing each stage. [La^-] was measured using the stationary Biosen C-Line lactate analyzer (Biosen, EKF Industrial Electronics, Magdeburg, Germany). In addition, gross efficiency was measured for the submaximal roller-ski stages and defined as the ratio of work and metabolic rate.[18] For the incremental test to exhaustion, respiratory variables and HR were measured continuously, and $VO_{2max/peak}$ defined as the highest 1-min average. HR_{max} was defined as the highest 5-sec HR measurement, whereas RPE was determined directly after, and [La^-] approximately 1 min after.

Statistical analysis

All data are reported as means ± standard deviations (SD). Assumption of normality was tested with a Shapiro–Wilk test in combination with visual inspection of histograms. Adopted from previous literature,[19,20] individual response magnitudes were summarized in three different categories: nonresponse defined as <0% change, moderate response as 0% to 5% change, and large response as >5% change. An adaptation index for each athlete was also calculated as the mean of the percentage change in treadmill running VO_{2max} and V_{peak}, treadmill roller-ski skating VO_{2peak} and V_{peak} from pre- to post.[20] To test for differences between groups, a univariate general linear model (GLM) analysis of covariance (ANCOVA) was used, with the percentage change from pre- to post as the dependent variable, and baseline values as a covariate to adjust for possible between-group differences pre-intervention. Pre- to post changes within groups were assessed using a paired-samples t-test. Between-group differences in baseline and training characteristics were tested using an independent-samples t-test. Effect size (ES) was calculated as Cohen's d by using the mean pre- to post change between groups, divided by the pooled pre-test SD (interpreted as follows: 0.0–0.24 trivial, 0.25–0.49 small, 0.5–1.0 moderate, >1.0 large).[21] 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 conducted using SPSS 26.0 (SPSS Inc, Chicago, IL, United States).

Results

Training characteristics

Comparisons of training characteristics between groups are shown in Table 2. Weekly TRIMP during the pre-intervention and intervention periods did not differ between groups ($p=0.60$ and $p=0.93$, respectively), whereas the training intensity distribution shifted from having a similar pattern across groups during the pre-intervention to clearly differing during the intervention. During the intervention period, LIG performed 16% more endurance training hours compared to HIG ($p<0.01$), due to 25% more hours of LIT ($p<0.01$). HIG performed 118% more hours of

HIT compared to LIG ($p<0.01$), whereas hours of MIT did not differ between groups ($p=0.35$). The volume of strength and speed training performed during the intervention period did not differ between groups ($p=0.67$ and 0.23, respectively).

Table 2 around here

Baseline characteristics and body mass

There were no differences between groups in age, anthropometrics, or any performance or physiological indices before the intervention. There were no between-group differences in body mass changes ($p=0.12$), although an increase was observed in HIG (1.9±2.2%, $p<0.01$) but not in LIG (0.5±2.1%, $p=0.19$).

Performance adaptations

There were no between-group differences in running TT performance changes ($p=0.44$), but HIG improved by -2.3±3.2% ($p=0.01$), with no change in LIG (-1.5±2.9%, $p=0.20$). The individual response magnitudes for TT performance changes are shown in Figure 2. The changes in treadmill running V_{peak} did not differ between groups ($p=0.30$) but were improved in HIG (2.2±3.1%, $p<0.01$), with a corresponding non-change in LIG (1.4±4.2%, $p=0.18$, Table 3). Treadmill roller-ski skating V_{peak} changes did not differ between groups ($p=0.20$) but were improved within both LIG and HIG (1.5±2.4% and 2.5±3.4%, respectively, both $p<0.01$).

Figure 2 around here

Table 3 around here

Physiological adaptations

There was a between-group difference in treadmill running VO_{2max} changes ($p=0.04$, Table 3), tending to improve in HIG (3.0±6.4%, $p=0.09$), with a corresponding non-change in LIG (-0.7±4.6%, $p=0.25$). There were no between-group differences in submaximal adaptations running at absolute speeds, although trivial to small effects of reduced RER, HR, $\%HR_{max}$, and RPE in HIG vs. LIG were found (see Table 3 for all details).

The change in treadmill roller-ski skating VO_{2peak} was different between groups ($p=0.02$), with improvements in HIG (3.6±5.4%, $p=0.01$) and a corresponding non-change in LIG (-0.1±4.0%, $p=0.62$). Overall, positive submaximal adaptations (i.e., $\%VO_{2max}$, RER, $\%HR_{max}$, and RPE) in roller-ski skating at absolute speeds were found in HIG and not in LIG, although gross efficiency was improved in both groups (see Table 4 for all details). Individual response magnitudes for V_{peak} and $VO_{2max/peak}$ in treadmill running and roller-ski skating are presented in Figure 3, while Figure 4 shows the adaptation index for each athlete in LIG and HIG.

Table 4 around here

Figure 3 around here

Figure 4 around here

Discussion

The present study compared the effects of increased load of LIT vs. HIT on performance and physiological adaptations in well-trained endurance athletes. The main findings were that performance adaptations, including uphill running TT performance and peak speed when incremental running and roller-ski skating to exhaustion in the laboratory, did not differ significantly between the two groups progressing their training with different endurance training intensities. However, while both groups improved their performance, increased load of HIT elicited 3–4% greater changes in running VO_{2max} and roller-ski skating VO_{2peak} compared to increased load of LIT.

In contrast to most previous intervention studies where endurance training load is matched for total work or oxygen consumption,[7-9] the present approach induced a similar increase in TRIMP load when progressing the overall training stimulus for both groups.[22,23] Accordingly, a significant between-group difference in LIT and HIT load was achieved while obtaining similar training loads. Although the intervention *per se* was regarded as successful because most athletes improved their performance, there are potential limitations with this approach caused by, e.g., between-athlete variations in adaptive signaling and stress tolerance to LIT and HIT training. In addition, this approach does not consider variations in metabolic vs. neuromuscular load between different training modalities (e.g., running vs. XC skiing). Although there was a change towards more specific training in the intervention period compared to baseline training, these changes were non-significant and similar between-groups. Accordingly, the design could be regarded valid for the purpose of the study.

With such matching of training load progression, the present study found little or no effects on performance adaptations in running or roller-ski skating when increasing the load of LIT vs. HIT in well-trained endurance athletes. Although the individual response magnitudes indicated more positive performance adaptations in HIG, the present statistical findings are in contrast to those of Stöggl and Sperlich[11] and Vesterinen et al.,[24] who demonstrated superior performance adaptations of a more polarized intensity distribution with greater HIT load compared to high-volume LIT regimes. However, Ingham et al.[25] and Nuuttila et al.[26] found similar performance adaptations of high-volume LIT and HIT regimes, which is in line with the present findings and implies that similar performance progression can be achieved both by increased load of LIT and HIT during the preparation period in endurance athletes.

In accordance with the hypothesis, increased load of HIT led to 3–4% better VO_{2max} adaptations in running and roller-ski skating compared to increased load of LIT. These findings were strengthened by the greater individual response magnitudes and adaptation index as well as better submaximal adaptations (e.g., reduced HR) at absolute speeds in HIG. Better VO_{2max} adaptations in HIG are likely explained by increased O_2 delivery capacity,[5,6,12] supported by other short-term training intensification studies.[7-9] This argues that even when matching training load with a more ecologically valid method as employed here, a high HIT stimulus seems needed to stress the cardiovascular system sufficiently and will thereby increase VO_{2max} more than when compensating with increased load of LIT.[5,12] Still, only trivial to small effects in the differences in physiological adaptations were found, which is likely explained by the relatively high training status and the short intervention period.[27-29] Altogether, progressing the overall training stimulus by intensification seems favorable if the goal is to elicit VO_{2max} adaptations over a relatively short training period in well-trained endurance athletes. To what extent these adaptations can be transferred also to performance benefits over a longer timescale requires further examination.

The individual response magnitudes revealed that some athletes in LIG also improved their VO_{2max} to the same extent as HIG, indicating individual variations in how athletes respond to different endurance training in eliciting VO_{2max}.[24,30] The present sample of athletes, including both sexes and different initial levels, could in part have contributed to the subsequent variations in training response. However, the groups were matched for sex and physiological indices pre-intervention, and baseline values were adjusted for as a covariate in the statistical analysis. In this context, no significant sex-differences in any performance or physiological adaptations were found. Accordingly, the present group comparisons are likely valid, although future studies should further investigate individual responses to changes in training volume and intensity distribution, as well as overall load adjustments in endurance athletes.

It seems obvious that improved VO_{2max} had a positive effect on performance adaptations in HIG. However, the reasons for improved performance in LIG without improving VO_{2max} could be explained by increased fractional utilization of VO_{2max} (i.e., anaerobic threshold). In this context, an interesting feature is that the number of LIT sessions above 2.5 hours in LIG might have provided a different stimulus for adaptive signaling than shorter LIT sessions. Accordingly, the hypothesis was that LIT and HIT induce complementary adaptations, which is partly induced through different molecular pathways.[1,5] However, this remains speculative as muscle biopsies or other measures to examine underlying mechanisms were not included in the present design.

Practical applications

The data presented in this study provide novel information with relevance for optimizing the training volume and intensity distribution in periods when the overall training stimulus is progressed in endurance athletes. The present data indicate that performance progression can be achieved both by increased load of LIT and HIT, although a sufficient HIT stimulus seems to be beneficial for eliciting maximal energy delivery capacities in 8 weeks. However, the more long-term effects and the effect of different periodization models of LIT and HIT focus prior to the competition period require further attention in future studies.

Conclusions

The present study found no significant difference in performance adaptations in running or roller-ski skating during 8 weeks of increased load of LIT vs. HIT in well-trained endurance athletes, although both methods improved performance. However, increased load of HIT elicited better VO_{2max} adaptations compared to increased load of LIT.

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Figure legends

Figure 1 – Training program for 8 weeks of **(A)** low-intensity training group and **(B)** high-intensity training group, including weekly distribution of moderate- (MIT) and high-intensity training (HIT) sessions and overall training load (TRIMP) within three different mesocycle loads (low, moderate, and high)

Figure 2 – Individual response magnitude for pre- to post changes in uphill running time trial performance summarized in three different categories: nonresponse (white), <0% change; moderate response (grey), 0–5% change; and large response (black) >5% change

Figure 3 – Individual response magnitude for pre- to post changes summarized in three different categories: nonresponse (white), <0% change; moderate response (grey), 0–5% change; and large response (black) >5% change. **(A)** Maximal oxygen uptake in treadmill running, **(B)** peak speed in treadmill running, **(C)** peak oxygen uptake in treadmill roller-ski skating, **(D)** peak speed in treadmill roller-ski skating

Figure 4 – Adaptation index for each individual athlete in **(A)** low-intensity training group and **(B)** high-intensity training group, calculated as the mean of the percentage change in maximal oxygen uptake and peak speed in treadmill running and peak oxygen uptake and peak speed in treadmill roller-ski skating from pre- to post

Table 1. Baseline characteristics of the 51 well-trained endurance athletes participating in the study (mean ± SD)

Variables	Men (n = 36)	Women (n = 15)	Total (n = 51)
Age (y)	17 ± 1	17 ± 0	18 ± 1
Body height (cm)	181.3 ± 0.7	167.2 ± 3.6	177.1 ± 8.2
Body mass (kg)	72.7 ± 7.1	62.0 ± 5.4	69.6 ± 8.2
Body mass index ($kg \cdot m^{-2}$)	22.1 ± 1.6	22.2 ± 2.2	22.1 ± 1.8
RUN-VO_{2max} ($L \cdot min^{-1}$)	5.08 ± 0.56	3.48 ± 0.35	4.59 ± 0.90
RUN-VO_{2max} ($mL \cdot min^{-1} \cdot kg^{-1}$)	70.3 ± 4.5	56.0 ± 3.4	65.9 ± 7.8
SKATE-VO_{2peak} ($L \cdot min^{-1}$)	4.86 ± 0.55	3.32 ± 0.36	4.41 ± 0.86
SKATE-VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)	66.8 ± 4.9	53.7 ± 3.9	62.9 ± 7.6
Annual training volume ($h\ y^{-1}$)	529 ± 95	493 ± 103	511 ± 99

RUN-VO_{2max}, maximal oxygen uptake in running; SKATE-VO_{2peak}, peak oxygen uptake in roller-ski skating.

Table 2. Training characteristics during an 8-week baseline and 8-week intervention period among 42 well-trained endurance athletes, randomized into either LIG or HIG (mean ± SD)

	8-week baseline period		**8-week intervention period**	
	LIG (n=22)	**HIG (n=20)**	**LIG (n=22)**	**HIG (n=20)**
Training forms				
Training volume (h)	97.0 ± 14.2	96.3 ± 18.1	108.7 ± 10.7*	94.8 ± 11.6#
Sessions (n)	60.7 ± 8.1	61.2 ± 9.9	67.0 ± 5.6*	67.0 ± 7.1*
Sickness/injury (d)	1.3 ± 2.6	0.6 ± 1.6	1.8 ± 2.8	1.7 ± 2.7
Training forms				
Endurance (h)	87.0 ± 12.9	84.7 ± 19.1	95.6 ± 9.3*	82.5 ± 10.4#
Strength (h)	7.7 ± 3.3	8.4 ± 1.8	9.0 ± 2.2	8.8 ± 2.0
Speed (h)	2.3 ± 1.1	3.2 ± 0.9#	4.1 ± 2.1	3.5 ± 1.0
Training mode				
Specific (h)[a]	40.5 ± 13.4	41.3 ± 9.6	52.6 ± 8.6*	43.7 ± 9.4
Non-specific (h)[b]	45.1 ± 9.2	43.2 ± 9.5	43.0 ± 7.9	38.8 ± 9.0
Specific/non-specific (%)	47/53	49/51	55/45	53/47
Endurance training volume				
Compliance (%TRIMP)	NaN	NaN	98 ± 9	100 ± 7
Load (TRIMP/wk)	729 ± 98	725 ± 157	781 ± 80*	779 ± 87
Load (TRIMP)	5831 ± 781	5804 ± 1257	6249 ± 640*	6230 ± 696
LIT load (TRIMP)	4649 ± 630	4586 ± 1121	5092 ± 587*	4303 ± 665#
MIT load (TRIMP)	489 ± 214	258 ± 237	434 ± 69	403 ± 122
HIT load (TRIMP)	703 ± 269	760 ± 204	723 ± 133	1523 ± 193*#
LIT (h)	78.8 ± 11.7	76.3 ± 18.8	88.0 ± 9.1*	70.4 ± 10.0#
MIT (h)	4.2 ± 1.8	3.8 ± 2.0	3.6 ± 0.6	3.4 ± 1.0
HIT (h)	4.0 ± 1.5	3.8 ± 1.3	4.0 ± 0.7	8.7 ± 1.0*#
LIT/MIT/HIT (%)	90/5/5	90/5/5	92/4/4	85/4/11
Endurance training sessions				
LIT (n)	39.9 ± 4.8	37.9 ± 7.0	44.9 ± 4.1*	37.1 ± 5.6#
LIT sessions ≥150 min (n)	7.1 ± 2.2	6.7 ± 2.3	10.3 ± 2.2*	2.3 ± 1.4*#
MIT (n)	5.6 ± 2.2	6.1 ± 2.4	4.9 ± 0.8	4.1 ± 1.1*#
HIT (n)	7.1 ± 2.2	8.6 ± 1.7	6.8 ± 1.0	15.6 ± 1.7*#
LIT/MIT/HIT (%)	76/11/13	72/11/16	80/9/11	65/7/28

LIG, low-intensity training group; HIG, 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. [a] classical and skating roller skiing; [b] running and cycling. *Significantly different from baseline period (*p<0.05) #Significantly different from LIG (#p<0.05).

Table 3. Anthropometrics and TT performance as well as performance and physiological indices during treadmill running at pre- and post-intervention in 42 well-trained endurance athletes, randomized into either LIG or HIG (mean ± SD)

	LIG (n=22)		HIG (n=20)		LIG vs. HIG
	Pre	**Post**	**Pre**	**Post**	**ES**
Anthropometrics					
Body mass (kg)	70.8 ± 7.5	71.2 ± 8.0	67.5 ± 7.9	68.8 ± 7.7*	0.10
Body mass index ($kg \cdot m^{-2}$)	22.5 ± 1.6	22.6 ± 1.6	21.4 ± 1.6	21.8 ± 1.6*	0.19
TT performance (4.5/6.4-km)					
Mean finishing time (s)	27:14	26:49	28:06	27:31	0.06
RUN submaximal (7/8-$km \cdot h^{-1}$)					
VO_2 ($L \cdot min^{-1}$)	3.28 ± 0.46	3.20 ± 0.45	3.13 ± 0.43	3.16 ± 0.44*#	0.22
VO_2 in % VO_{2max}	70.9 ± 6.2	69.9 ± 6.2	69.7 ± 5.5	68.3 ± 4.6	0.07
RER	0.91 ± 0.04	0.91 ± 0.03	0.92 ± 0.05	0.90 ± 0.03*	0.75
HR ($beats \cdot min^{-1}$)	167 ± 12	165 ± 11	164 ± 10	160 ± 8	0.27
HR in %HR_{max}	83.2 ± 4.8	82.2 ± 4.7	82.9 ± 4.2	80.5 ± 4.1	0.29
Borg (6-20)	12.7 ± 1.3	12.4 ± 1.6	12.8 ± 1.4	12.2 ± 1.1	0.21
$[La^-]$ ($mmol \cdot L^{-1}$)	2.12 ± 0.84	1.90 ± 0.58	2.27 ± 0.90	2.02 ± 0.74*	0.03
RUN TTE					
VO_{2max} ($L \cdot min^{-1}$)	4.68 ± 0.92	4.63 ± 0.83	4.54 ± 0.80	4.64 ± 0.81#	0.18
VO_{2max} ($mL \cdot min^{-1} \cdot kg^{-1}$)	65.7 ± 7.6	64.7 ± 6.3	66.7 ± 7.1	67.4 ± 6.2#	0.22
RER	1.13 ± 0.04	1.15 ± 0.04	1.14 ± 0.05	1.14 ± 0.04	0.30
HR_{max} ($beats \cdot min^{-1}$)	199 ± 6	199 ± 7	197 ± 9	197 ± 8	0.02
$[La^-]$ ($mmol \cdot L^{-1}$)	11.02 ± 1.49	11.57 ± 1.91	11.48 ± 1.78	11.92 ± 1.88	0.06
TTE (s)	350 ± 63	360 ± 57	359 ± 55	381 ± 45*	0.36
V_{peak} ($km \cdot h^{-1}$)	14.5 ± 1.4	14.7 ± 1.3	14.8 ± 1.2	15.1 ± 1.1*	0.10

TT, time trial; LIG, low-intensity training group; HIG, high-intensity training group; ES, effect size; RUN, laboratory test running; 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. *Significantly different from pre (*$p < 0.05$). #Significantly different from pre- to post change in LIG (#$p<0.05$).

Table 4. Performance and physiological indices obtained during treadmill roller-ski skating at pre and post-intervention in 42 well-trained endurance athletes, randomized into either LIG or HIG (mean ± SD)

	LIG (n=22)		**HIG (n=20)**		**LIG vs. HIG**
	Pre	**Post**	**Pre**	**Post**	**ES**
SKATE submaximal (10/12-km·h^{-1})					
VO_2 (L·min^{-1})	3.19 ± 0.51	3.12 ± 0.49*	3.05 ± 0.42	3.03 ± 0.39	0.10
VO_2 in % VO_{2peak}	71.8 ± 5.3	70.3 ± 4.4*	71.6 ± 5.9	68.8 ± 4.7*	0.29
RER	0.93 ± 0.03	0.91 ± 0.03	0.95 ± 0.05	0.94 ± 0.03*	0.13
HR (beats·min^{-1})	173 ± 10	173 ± 9	170 ± 10	167 ± 9*#	0.32
HR in %HR_{max}	86.4 ± 4.2	86.5 ± 3.3	86.2 ± 3.8	84.5 ± 3.4*#	0.40
Borg (6-20)	11.2 ± 1.9	11.6 ± 1.8	11.9 ± 1.2	11.8 ± 1.7	0.44
[La$^-$] (mmol·L^{-1})	2.72 ± 0.91	2.79 ± 0.77	3.06 ± 1.21	2.82 ± 0.77	0.27
GE (%)	13.8 ± 0.6	14.2 ± 0.6*	13.9 ± 0.8	14.3 ± 0.6*	0.08
SKATE submaximal (12/14-km·h^{-1})					
VO_2 (L·min^{-1})	3.57 ± 0.55	3.52 ± 0.52	3.44 ± 0.47	3.42 ± 0.43	0.08
VO_2 in % VO_{2peak}	80.6 ± 5.6	79.5 ± 4.5	80.7 ± 4.8	77.6 ± 4.9*#	0.41
RER	0.96 ± 0.04	0.95 ± 0.03	0.97 ± 0.03	0.96 ± 0.04*	0.15
HR (beats·min^{-1})	184 ± 9	183 ± 7	180 ± 11	178 ± 9*	0.12
HR in %HR_{max}	92.0 ± 3.2	91.5 ± 2.2	91.4 ± 3.7	90.3 ± 3.0*	0.17
Borg (6-20)	14.4 ± 1.3	14.1 ± 1.4	14.6 ± 1.2	13.9 ± 1.2*	0.31
[La$^-$] (mmol·L^{-1})	4.11 ± 1.37	4.09 ± 1.11	4.28 ± 2.01	4.17 ± 1.27	0.05
GE (%)	14.3 ± 0.6	14.6 ± 0.3*	14.4 ± 0.7	14.7 ± 0.6*	0.01
SKATE TTE					
VO_{2peak} (L·min^{-1})	4.48 ± 0.89	4.46 ± 0.84	4.30 ± 0.72	4.43 ± 0.67*#	0.18
VO_{2peak} (mL·min^{-1}·kg^{-1})	62.8 ± 7.0	62.5 ± 6.5	63.4 ± 6.7	64.4 ± 5.8#	0.18
RER	1.11 ± 0.05	1.11 ± 0.04	1.11 ± 0.05	1.11 ± 0.05	0.01
HR_{peak} (beats·min^{-1})	198 ± 7	199 ± 7	196 ± 8	196 ± 7	0.10
[La$^-$] (mmol·L^{-1})	10.84 ± 1.66	11.16 ± 2.17	10.78 ± 1.60	10.92 ± 1.83	0.12
TTE (s)	281 ± 56	299 ± 56*	292 ± 71	322 ± 58*	0.18
V_{peak} (km·h^{-1})	21.0 ± 1.6	21.3 ± 1.6*	21.4 ± 1.8	21.9 ± 1.6*	0.11

LIG, low-intensity training group; HIG, high-intensity training group; ES, effect size; SKATE, laboratory test roller-ski skating; 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; *Significantly different from pre (*$p < 0.05$). #Significantly different from pre- to post change in LIG (#$p<0.05$).

Figure 1.

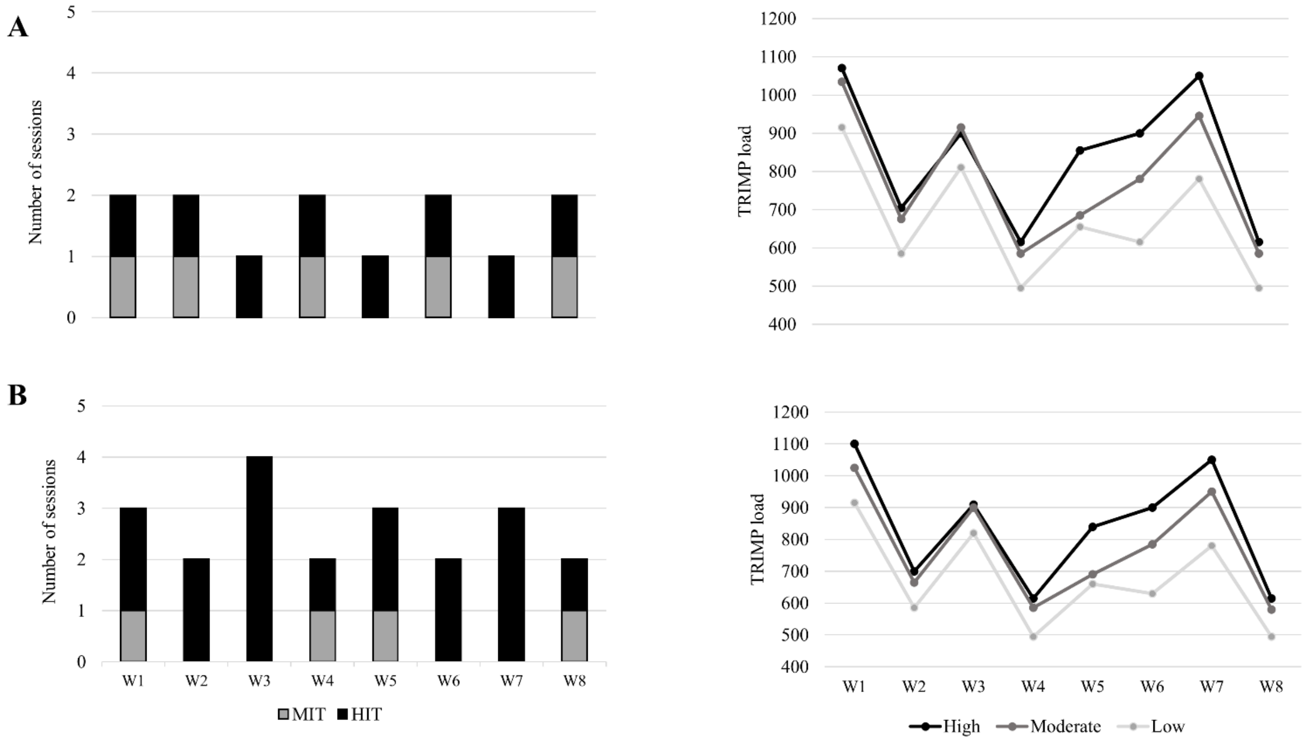

Figure 2.

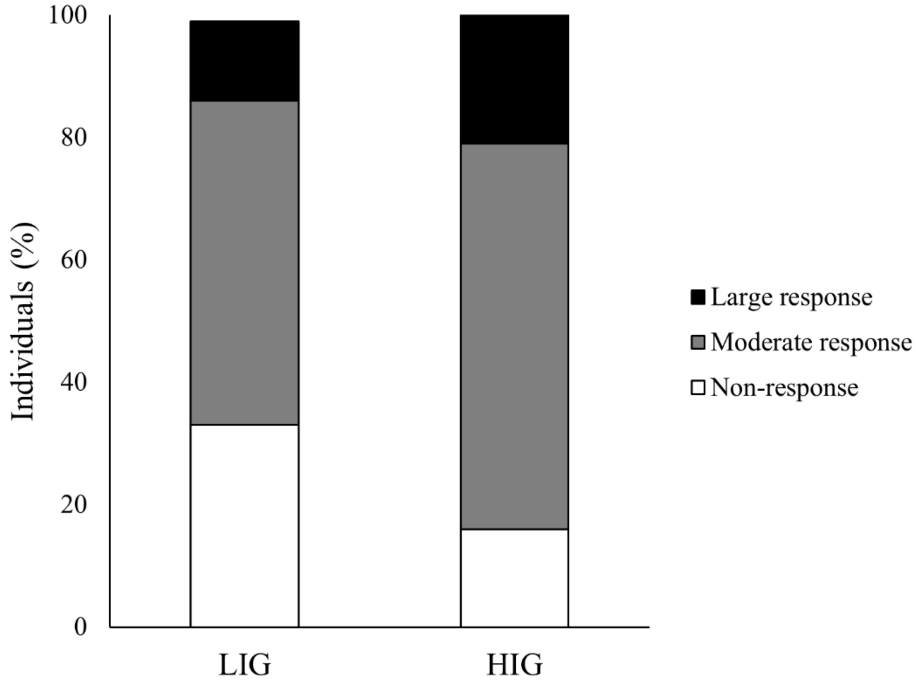

Figure 3.

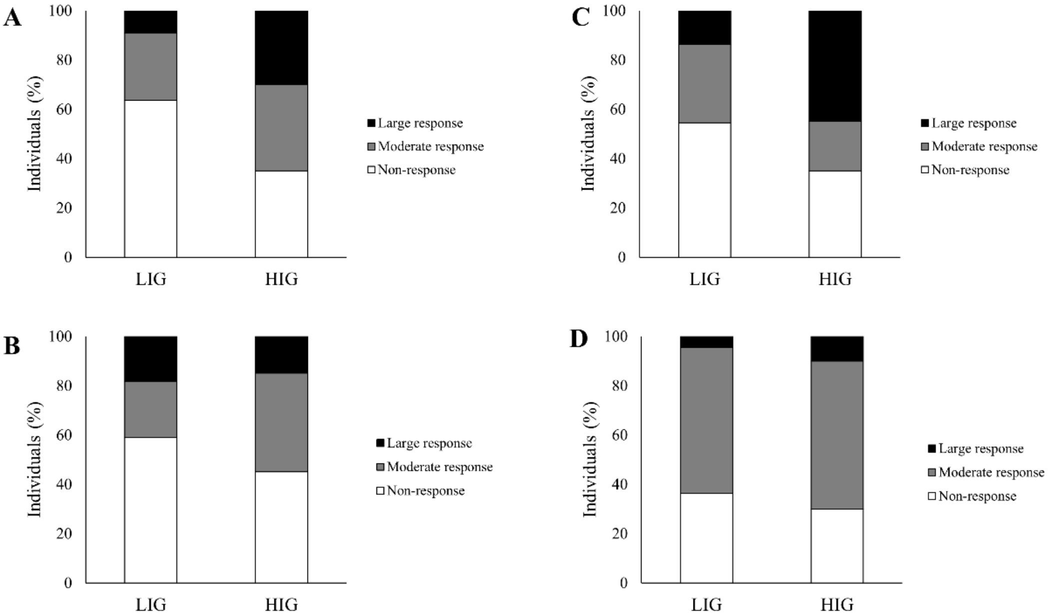

Figure 4.