Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training

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INTRODUCTION
Athletes participating in endurance sports such as running, cycling, and cross-country skiing integrate four conditioning concepts into their training programs to maximize athletic performance. The first conditioning concept is prolonged high-volume low-intensity exercise (HVT). The second is training at or near the lactate threshold (THR); third is low-volume high-intensity interval training (HIIT) and the fourth concept is a combination of these aforementioned concepts known as polarized training (POL).

The purpose of this study was to explore which of these four training concepts provides the greatest response on key components of endurance performance in well-trained endurance athletes.

Methods: Forty eight runners, cyclists, triathletes, and cross-country skiers (peak oxygen uptake: (VO2peak): 62.6 ± 7.1 mL·min⁻¹·kg⁻¹) were randomly assigned to one of four groups performing over 9 weeks. An incremental test, work economy and a VO2peak tests were performed. Training intensity was heart rate controlled.

Results: POL demonstrated the greatest increase in VO2peak (+6.8 ml·min·kg⁻¹ or 11.7%, P < 0.001), time to exhaustion during the ramp protocol (+17.4%, P < 0.001) and peak velocity/power (+5.1%, P < 0.01). Velocity/power at 4 mmol·L⁻¹ increased after POL (+8.1%, P < 0.01) and HIIT (+5.6%, P < 0.05).

No differences in pre- to post-changes of work economy were found between the groups. Body mass was reduced by 3.7% (P < 0.001) following HIIT, with no changes in the other groups. With the exception of slight improvements in work economy in THR, both HVT and THR had no further effects on measured variables of endurance performance (P > 0.05).

Conclusion: POL resulted in the greatest improvements in most key variables of endurance performance in well-trained endurance athletes. THR or HVT did not lead to further improvements in performance related variables.

Keywords: lactate threshold, peak power, peak oxygen uptake, time to exhaustion, work economy
improvements in running speed at lactate threshold and performance in a 20-min run when exercising at an intensity eliciting 3–4 mmol L\(^{-1}\) lactate compared with low intensity training (<3–4 mmol L\(^{-1}\)) were found (Evertsen et al., 2001). In contrast, experimental and correlational data from well-trained athletes suggest that training time close to LT may be ineffective, or even counterproductive (Esteve-Lanao et al., 2007; Guelfic and Seiler, 2010).

Retrospective analysis of the intensity, duration and frequency of the training load of international-level cross-country skiers (Seiler and Kjerland, 2006), rowers (Steinacker et al., 1998), cyclists (Schumacher and Mueller, 2002), and runners (Billat et al., 2001; Esteve-Lanao et al., 2005) revealed that elite endurance athletes completed most of their yearly training sessions at either intensities below (~75%) of total training volume) or well above (~15–20%) of total training volume) their LT. Six weeks of cycling using POL resulted in greater systemic adaptation in already well-trained athletes when compared to THR (Neal et al., 2013). However, no study has investigated the POL concept in well-trained endurance athletes to determine whether this concept may be superior to the aforementioned training strategies.

In many endurance sports, five key variables have been used as a benchmark to compare athletic performance in and between endurance athletes: (i) VO\(_{2}\)peak (Bassett and Howley, 2000); (ii) velocity/power output at the lactate threshold (V/P\(_{LT}\)) (Bassett and Howley, 2000; Midgley et al., 2007; Faude et al., 2009); (iii) work economy (Di Prampero et al., 1986; Helgerud et al., 2001); (iv) peak running velocity or power output (V/P\(_{peak}\)) (Midgley et al., 2007); and (v) time to exhaustion (TTE) (Laursen and Jenkins, 2002). The aim of this study was to compare the effects of four training concepts (HVT vs. THR vs. HIIT vs. POL) on the aforementioned key variables of endurance performance in well-trained athletes. We hypothesized that the POL and HIIT group would lead to superior improvements compared with HVT and THR.

**MATERIALS AND METHODS**

**PARTICIPANTS**

Forty eight healthy competitive endurance athletes 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 years, body mass: 73.8 ± 9 kg, height: 180 ± 8 cm). All participants were well-trained [62.6 ± 7.1 mL·min\(^{-1}\)·kg\(^{-1}\) (range: 52–75 mL·min\(^{-1}\)·kg\(^{-1}\))] athletes, accustomed to a workload of more than five sessions per week (10–20 h·wk\(^{-1}\)) and had frequently been involved in endurance competitions for at least 8–20 years. Participants were members of the Austrian cross-country skiing national team (n = 8), running (n = 21), triathlon (n = 4) or cycling (n = 15) teams during or since the year before the current study. Retrospective analysis of training protocols over 6 months prior to the study revealed that none of the participants had regularly executed HIIT. All had followed a HVT training protocol with a maximum of two THR training sessions per week.

Based on the participants’ baseline VO\(_{2}\)peak and training mode (running or cycling), all athletes were randomized into HIIT, HVT, THR or POL. At baseline, the four groups were not statistically different with regard to age, height, body mass or VO\(_{2}\)peak. During an initial visit, study details and participation requirements were explained, and written informed consent was obtained. The study 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 (n = 15 cyclists; n = 3 triathletes) engaging in cycling training 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 (n = 16 runners, n = 6 triathletes, n = 8 cross-country skiers) 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 (HR at blood lactate value <2 mmol·L\(^{-1}\)); (ii) LT (HR corresponding to a blood lactate of 3–5 mmol·L\(^{-1}\)); (iii) HIGH (>90% HRR\(_{peak}\)). 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.

**HVT INTERVENTION**

The HVT included three blocks each lasting 3 weeks: 2 weeks of high-volume training followed by 1 week of recovery (Figure 1A). The two high volume weeks each included six training sessions with three 90 min LOW sessions, two 150–240 min LOW sessions (according to the training mode: running, cycling, or roller skiing) and one 60 min LT session using different types of interval training (e.g., 5 × 7 min with 2 min recovery, 3 × 15 min with 3 min recovery). The recovery week included three training sessions with two 90 min LOW sessions and one 150–180 min LOW session.

**THR INTERVENTION**

The THR included three blocks, each lasting 3 weeks: 2 weeks of high volume and intensity training followed by 1 week of recovery (Figure 1B). The two high volume and intensity weeks each included six training sessions with two 60 min interval sessions at the LT (5 × 6 min and 2 min recovery in the first block, 6 × 7 min in the second block and 6 × 8 min in the last block), one 90 min LT session with longer intervals (3 × 15 min with 3 min active recovery in the first block and 3 × 20 min for the remaining two blocks), one 75 min session with varying changes in intensity (“fartlek”) (intensities resulting in a blood lactate of 1.5–5 mmol·L\(^{-1}\)) and two 90 min LOW sessions. The recovery week included one 60 min LOW session and two 60 min LT interval sessions (5 × 6 min with 2 min of active recovery).
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 LOW sessions, one 120 min LOW 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 three consecutive days followed by 1 day of recovery. The recovery week contained four LOW sessions of 90 min and 3 days without any training (not presented in Figure 1D).

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 (Figure 1C). The high volume and intensity week included six sessions with two 60 min HIIT sessions, two 150–240 min long duration LOW 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 LOW sessions. The recovery week included one 60 min HIIT session, one 120–180 min LOW session and one 90 min LOW session.

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 the determination of body mass, an incremental test protocol, a work economy and VO2peak ramp protocol.

On the first day participants performed an incremental test on a treadmill (7.2 km·h⁻¹; increment: 1.8 km·h⁻¹ every 5 min, with 30 s recovery between stages, inclination 1%) or cycle ergometer (80 W; increment: 40 W every 5 min, cadence >80 rpm) until volitional exhaustion was achieved to assess the peak velocity/power output (V/Ppeak), HR, blood lactate, as well as the velocity, power output and HR at 2 and 4 mmol·L⁻¹ blood lactate (V/P₂, V/P₄ and HR₂, HR₄). The participants’ HR was recorded by telemetry (Suunto t6, Helsinki, Finland) at 2-s intervals. The mean HR over the last 30 s of each increment was used for statistical analysis. A 20 µl blood sample from the right earlobe was collected immediately after each increment, as well as 3 and 5 min after the completion of the test 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.

One day after the incremental tests, all athletes completed a combined work economy and VO$_2$peak ramp protocol to determine their submaximal and peak VO$_2$ (VO$_2$submax and VO$_2$peak) and HR (HR$_{submax}$ and HR$_{peak}$), as well as time to exhaustion (TTE). The overall time for the ramp test was defined as time combined work economy and VO$_2$peak ramp protocol to determine VO$_2$submax and HR$_{submax}$ for this intensity. The mean VO$_2$ and HR during the last 5 min of these tests were used for statistical purposes. The intensity 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. The overall time for the ramp test was defined as time to exhaustion (TTE). 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 1L syringe (nSpire, Oberthulba, Germany). All respiratory data were averaged every 30 s. VO$_2$peak was achieved if three of the four following criteria were met: (1) plateau in VO$_2$, i.e., an increase < 1.0 mL·min$^{-1}$·kg$^{-1}$ despite an increase in velocity or power output; (2) respiratory exchange ratio > 1.1; (3) HR ± 5% of age predicted HR$_{peak}$; and (4) peak blood lactate (LA$_{peak}$) > 6 mmol·L$^{-1}$ after exercise. Reliability analysis of The VO$_2$peak test (n = 18) revealed ICC values of 0.96 for VO$_2$peak and 0.98 for TTE.

**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 × 4 repeated-measures ANOVA (2 times: pre- to post-training, 4 groups) to test for global differences between pre- and post-intervention, the four training groups and the interaction effect between both factors was applied. When a significant main effect over time was observed, paired t-tests within each group were conducted. Based on the different units of peak power/velocity and power/velocity at 2 and 4 mmol·L$^{-1}$ blood lactate in the incremental and VO$_2$peak test, percent changes between pre- to post-values were calculated, and a One-Way ANOVA between groups was performed using Tukey’s post-hoc analysis. Furthermore, within group changes for these variables were calculated using Wilcoxon tests. An alpha value of < 0.05 was considered significant. The Statistical Package for the Social Sciences (Version 20.0; SPSS Inc., Chicago, IL, USA) and Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA) were used for statistical analysis.

**RESULTS**

Forty-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, 1 in HVT and 4 in THR) withdrew from the study due to illness (n = 2), or were excluded due to changes in competition schedule (n = 3) or for not fulfilling the training protocol (n = 2). The total training hours, number of training sessions and their percent distribution within LOW, LTP, and HIIT are presented in Table 1. POL and HVT had higher training volume compared with THR and HIIT (P < 0.05–0.001), while having a similar number of training sessions (P > 0.05). HVT demonstrated the greatest amount of LOW, THR of LT, and HIIT in HIGH training sessions (all, P < 0.05).

Body mass after HIIT was reduced by 3.7 ± 3.0% (baseline: 73.5 ± 6.8 kg, post: 70.7 ± 6.5 kg, P < 0.01) with no significant change in the HVT, THR or POL groups. The reduction in body mass after HIIT was greater compared to other training interventions (P < 0.001).

Percent changes in variables from pre- to post-training and between the training concepts during the VO$_2$peak-ramp, work economy, and incremental tests are presented in Table 2. POL demonstrated the greatest increase in VO$_2$peak.

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**Table 1** | The distribution of volume and training intensity within the 9 weeks training intervention (excluding strength training).

|                  | POL       | HIIT      | THR       | HVT       | F-Value | P-Value |
|------------------|-----------|-----------|-----------|-----------|---------|---------|
| Total hours      | 104 ± 20 $\frac{\%}{\text{±}}$ | 66 ± 1 $\frac{\%}{\text{±}}$ | 84 ± 7 $\frac{\%}{\text{±}}$ | 102 ± 11 $\frac{\%}{\text{±}}$ | $^a F(3, 37) = 20$ | <0.001 |
| Number of sessions | 54 ± 3 | 47 ± 1 | 49 ± 3 | 58 ± 3 | $^a F(3, 37) = 1.6$ | n.s. |
| Amount of training at low intensity (%) | 37 ± 9 (68 ± 12 %)$\frac{\%}{\text{±}}$ | 20 ± 1 (43 ± 1 %)$\frac{\%}{\text{±}}$ | 23 ± 6 (46 ± 7 %)$\frac{\%}{\text{±}}$ | 49 ± 7 (83 ± 6 %)$\frac{\%}{\text{±}}$ | $^a F(3, 37) = 41$ | <0.001 |
| Amount of training at lactate threshold (%) | 3 ± 4 (6 ± 8 %)$\frac{\%}{\text{±}}$ | 0 (0 %)$\frac{\%}{\text{±}}$ | 26 ± 2 (54 ± 7 %)$\frac{\%}{\text{±}}$ | 9 ± 3 (16 ± 6 %)$\frac{\%}{\text{±}}$ | $^a F(3, 37) = 197$ | <0.001 |
| Amount of training at high intensity (%) | 14 ± 3 (26 ± 7 %)$\frac{\%}{\text{±}}$ | 27 ± 1 (87 ± 1 %)$\frac{\%}{\text{±}}$ | 0 (0 %)$\frac{\%}{\text{±}}$ | 1 ± 1 (1 ± 1 %)$\frac{\%}{\text{±}}$ | $^a F(3, 37) = 769$ | <0.001 |

The values presented are means ± SD. F- and P-values were obtained by One-Way ANOVA (4 training groups). POL, polarized training group; HIIT, High intensity interval training group; THR, threshold training group; HVT, high volume training group.

$^a$Different from all other groups.

$^\dag$Different from training group “POL.”

$^\ddag$Different from training group “HIIT.”

$^*\ddag$Different from training group “THR.”

$^\ddagger$Different from training group “HVT.”

$^\ast$Main effect between groups n.s., not significant.
Table 2 | Changes in physiological variables from pre- to post-training.

|                | POL          |          | HIIT         |          | THR          |          | HVT          |          | F-Value | P-Value |
|----------------|--------------|----------|--------------|----------|--------------|----------|--------------|----------|---------|---------|
|                | Pre          | Post     | Pre          | Post     | Pre          | Post     | Pre          | Post     |         |         |
| **VO2peak**    | 60.6±8.3     | 67.4±7.7*** | 63.7±7.1     | 66.6±5.8* | 63.2±4.6     | 60.8±7.1 | 60.5±9.4     | 62.1±9.8 |         |         |
| (L-min⁻¹·kg⁻¹) | 11.7±8.4%    |          | 4.8±5.6%     |          | −4.1±6.7%††† |          | 2.6±4.5%†    |          |         | <0.001 |
| **VO2peak**    | 4.4±1.0      | 4.9±1.1*** | 4.6±0.5      | 4.7±4.9  | 4.4±0.8      | 4.3±9.2  | 4.8±0.7      | 4.9±0.7  |         | <0.001 |
| (L-min⁻¹)      | 10.4±7.9%    |          | 1.1±7.6%†    |          | −3.7±7.0%††† |          | 2.9±4.5%†    |          |         | < 0.05 |
| **HRpeak**     | 187±7        | 186±7    | 185±9        | 182±11   | 180±10       | 179±9    | 183±4        | 183±4    |         | NS      |
| [bpm]          | −0.6±1.9%    |          | −1.3±2.3%    |          | −0.2±1.9%    |          | 0.3±1.9%     |          |         | NS      |
| **LApeak**     | 10.2±1.7     | 10.7±1.7 | 9.6±1.7      | 10.2±1.7 | 9.5±1.6      | 9.9±2.2  | 10.1±1.7     | 9.9±2.0  |         | NS      |
| [mmol·L⁻¹]     | 7.5±20.4%    |          | 6.4±8.3%     |          | 5.3±19.1%    |          | −1.0±11.8%   |          |         | NS      |
| **VO2submax**  | 38.2±5.5     | 39.7±5.0 | 34.8±6.1     | 35.9±6.2 | 34.7±5.1     | 33.7±4.4 | 35.2±4.4     | 35.3±4.7 |         | NS      |
| (mL·min⁻¹·kg⁻¹)| 4.6±10.5%    |          | 3.8±12.0%    |          | −2.1±7.8     |          | 0.6±9.5%     |          |         | NS      |
| **HRsubmax**   | 136±10       | 135±13   | 141±13       | 131±6**  | 143±3        | 139±3*  | 136±7        | 134±5    |         | <0.01   |
| [bpm]          | −3.3±6.4%    |          | −6.7±4.4%    |          | −2.7±1.0     |          | −1.1±3.4%    |          |         |         |
| **Work economy** | 74.3±5.4    | 72.5±6.3 | 76.1±4.7     | 71.9±2.2* | 77.8±3.6     | 75.8±3.9** | 74.2±2.1     | 73.0±1.6 |         | < 0.01 |
| [%HRpeak]      | −2.4±6.3%    |          | −5.4±4.5%    |          | −2.6±0.9     |          | −1.6±2.0%    |          |         | NS      |

(Continued)
The values presented are means ± SD for all measures (training group) with repeated measures. POL, polarized training group; HIIT, high intensity interval training group; THR, threshold training group; HVT, high volume training group. Work economy (protein concentration in plasma, % peak) was decrease in THR (± 1.7% decrease in HR, < 0.05) and THR (± 1.0% decrease in HR, P < 0.05) with no significant differences between the other concepts. Work economy expressed as percent of VO_{peak} was only improved after POL (± 4.8 %, P < 0.05) with no significant differences between the other training groups.

The changes in TTE, V/P_{peak} and V/P_{2 & 4} from pre- to post-training and between the single training groups are presented in Table 3. The largest percentage increase in TTE, assessed using the VO_{peak} ramp test, was observed in response to POL (+17.4%, P < 0.001) followed by HIIT (+8.8%, P < 0.01); however, no statistical differences were found between the four training concepts. V/P_{peak} in the incremental test increased in response to POL and HIIT (5.1 ± 3.0% and 4.4 ± 2.8%, both P < 0.01) with both groups demonstrating greater changes than HVT (P < 0.05). V/P_{4} increased after POL (8.1 ± 4.6%, P < 0.01) and HIIT (5.6 ± 4.8%, P < 0.01) demonstrating greater changes after POL compared to THR and HVT (both P < 0.05).

**DISCUSSION**

The purpose was to determine whether HIIT, HVT, THR, or POL provides the greatest impact on key variables of endurance performance in well-trained athletes. The main findings were that (1) POL led to the greatest improvement in VO_{peak}, TTE and V/P_{peak}; (2) V/P_{4} increased after POL and HIIT; (3) no significant differences in work economy were observed pre to post between any of the groups; and finally (4) body mass decreased by 3.7% in response to HIIT.

There are several challenges associated with conducting an exercise training intervention such as the one presented here. Firstly, the compliance of all athletes is paramount to the successful completion of the study and for the subsequent examination of the intervention. The athletes attended more than 95% of all training sessions and all completed their predetermined training load (intensity based on HR zones, duration, and frequency), which was confirmed by logging the daily training dose in a diary and retrospective analysis of HR data. Secondly, an experimental study is difficult to conduct in elite athletes because typically neither the athletes nor their coaches like to have the athletes’ training intensity, duration or frequency altered. However, we successfully managed to conduct the current study in well-trained male and female athletes (VO_{peak}: 52–75 mL·min^{-1}·kg^{-1}) over a 9 week period.

Of the four training concepts, POL resulted in the greatest increase in VO_{peak}, TTE, V/P_{peak} and, together with HIIT, in V/P_{4}. As mentioned, POL was confirmed by retro-perspective analysis of the intensity, duration and frequency distribution of the training load in highly trained athletes (Steinacker et al.,...
response to HIIT explain the often documented increases in TTE, time trial performance (Lindsay et al., 1996), lactate and ventilatory threshold (Acevedo and Goldfarb, 1989; Edge et al., 2005) and VO\textsubscript{2peak} (Laursen and Jenkins, 2002; Gibala et al., 2006; Daussin et al., 2007, 2008; Burgomaster et al., 2008).

Table 3 | Per cent changes in velocity (V) and power (P) and at various lactate thresholds as well as peak velocity and power.

|              | POL     | HIIT    | THR     | HVT     | F-Value | P-Value |
|--------------|---------|---------|---------|---------|---------|---------|
| TTE          | 17.4±16.1*** | 8.8±8.6** | 6.2±9.0 | 8.0±10.3 | \textsuperscript{a}F\textsubscript{(3, 37)} = 2.0 | NS      |
| V/P\textsubscript{2} | 9.3±12.4 | 12.1±8.8** | 2.0±13.8 | 0.8±13.3 | \textsuperscript{a}F\textsubscript{(3, 37)} = 1.9 | NS      |
| V/P\textsubscript{4} | 8.1±4.8** | 5.6±4.8* | 1.4±4.3\textsuperscript{f} | 1.2±6.6\textsuperscript{f} | \textsuperscript{a}F\textsubscript{(3, 37)} = 4.5 | <0.01   |
| V/P\textsubscript{peak} | 5.1±3.0** | 4.4±2.8** | 1.8±4.8 | -1.5±4.9\textsuperscript{f} | \textsuperscript{a}F\textsubscript{(3, 37)} = 4.6 | <0.01   |

The values presented are means ± SD. F and P values were obtained by One-Way ANOVA (4 training groups) calculated over the per cent differences between pre- and post-training. POL, polarized training group; HIIT, High-intensity interval training group; THR, threshold training group; HVT, high-volume training group; TTE, time to exhaustion during the ramp test; V/P\textsubscript{2}, velocity or power at 2 mmol·L\textsuperscript{-1}; V/P\textsubscript{4}, velocity or power at 4 mmol·L\textsuperscript{-1}; V/P\textsubscript{peak}, peak velocity or power in the incremental test; \textsuperscript{a}F\textsubscript{(3, 37)} = 2.0 significant different from HIIT training group. \textsuperscript{f}p < 0.05 significant different from POL training group. \textsuperscript{†}p < 0.05 significant different from HIIT training group. \textsuperscript{‡}Main effect between groups.
remained fairly constant. V/P4 was only improved in POL (8.1%). HIIT led to a decrease in body mass and less pronounced improvements in VO2peak (Helgerud et al., 2001; McMillan et al., 2005). Despite the large differences in the individual responses in some of the training groups, none of the athletes demonstrated reduced TTE or V/Ppeak after the study, nor did they report any of the aforementioned symptoms during and after the 9 week intervention. Based on the observed changes in body mass and smaller increases in VO2peak in the HIIT group compared with previously published data (McMillan et al., 2005; Stolen et al., 2005; Helgerud et al., 2007), longer blocks of training periods with high intensities could provoke these symptoms.

Except for significant decreases in %VO2peak in the POL group and HRsubmax/%HRpeak in the HIIT and THR groups (with no group differences), no improvements in work economy were found in the current study. Helgerud et al. (2007) reported a ∼5% improvement in running economy after THR, HIIT, and HVT with no differences between groups. These improvements were mainly attributed to an increased amount of running training. Therefore, the applied training regimes were largely responsible for the changes in V/Ppeak and VO2peak, while work economy remained fairly constant. V/P4 was only improved in POL (8.1%) and HIIT (5.6%). This is consistent with findings demonstrating that running velocity at lactate threshold follows the improvements in VO2peak (Helgerud et al., 2001; McMillan et al., 2005).

LIMITATIONS AND PERSPECTIVES

Standardized methodology of performance diagnostics (incremental test and VO2peak ramp protocol) was utilized to evaluate the effects of the four endurance training interventions on key variables of endurance performance. However, a direct transfer to specific competition situation (e.g., time trial) need to be established in future research. Furthermore, the increase of about 11% in VO2peak with POL within 9 weeks is large for well-trained athletes since world-class sprint cross-country skiers demonstrated greater training volume in the low and moderate intensity zones compared with national-level skiers (Sandbakk et al., 2011).

The body mass of the well-trained athletes decreased by 3.7% (approximately 3 kg) after HIIT, but not in response to the other training concepts. HIIT favors lipid oxidation and promotes adipose tissue loss (Perry et al., 2008; Boutcher, 2011). Depending on the athlete's baseline value, reduction in body mass may negatively impact immune function and overall health, as well as induce a catabolic state. Training blocks with increased volume and/or exercise intensity might induce symptoms of “overreaching,” reduced physical capacity, burnout symptoms including tiredness, and lack of energy (Angeli et al., 2004). However, some THR training might be beneficial to well-trained athletes since world-class sprint cross-country skiers demonstrated greater training volume in the low and moderate intensity zones compared with national-level skiers (Sandbakk et al., 2011).

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AUTHOR CONTRIBUTIONS

Conception and design of the experiments: Thomas Stögg, Billy Sperlich. Performance of the experiments: Thomas Stögg. Data analysis: Thomas Stögg, Billy Sperlich. Preparation of the manuscript: Thomas Stögg and Billy Sperlich. Both authors read and approved the final manuscript.

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