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Adaptations to aerobic interval training: interactive effects of exercise intensity and total work duration

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To compare the effects of three 7-week interval training programs varying in work period duration but matched for effort in trained recreational cyclists. Thirty-five cyclists (29 male, 6 female, VO_{2peak} 52 ± 6 mL kg/min) were randomized to four training groups with equivalent training the previous 2 months (~ 6 h/wk, ~ 1.5 int. session/wk). Low only ($n = 8$) trained 4–6 sessions/wk at a low-intensity. Three groups ($n = 9$ each) trained 2 sessions/wk × 7 wk: 4 × 4 min, 4 × 8 min, or 4 × 16 min, plus 2–3 weekly low-intensity bouts. Interval sessions were prescribed at the maximal tolerable intensity. Interval training was performed at 88 ± 2, 90 ± 2, and 94 ± 2% of HR_{peak} and 4.9, 9.6, and 13.2 mmol/L blood lactate in 4 × 16, 4 × 8, and 4 × 4 min groups, respectively (both $P < 0.001$). 4 × 8min training induced greater overall gains in VO_2-peak, power@VO_2peak, and power@4 mM bLa- (Mean 95%CI): 11.4 (8.0–14.9), vs 4.2 (0.4–8.0), 5.6 (2.1–9.1), and 5.5% (2.0–9.0) in Low, 4 × 16, and 4 × 4 min groups, respectively ($P < 0.02$ for 4 × 8 min vs all other groups). Interval training intensity and accumulated duration interact to influence the adaptive response. Accumulating 32 min of work at 90% HR max induces greater adaptive gains than accumulating 16 min of work at ~ 95% HR max despite lower RPE.

Introduction

Endurance athletes vary the intensity and duration of their training from day to day. Once the work intensity exceeds that corresponding to the lactate threshold, relatively small changes in exercise intensity are associated with large changes in accumulated exercise duration (Seiler & Tønnessen, 2009; Seiler, 2010). The relative adaptive impact of accumulated duration and work intensity during interval training is not well established. Åstrand and Rodahl wrote "It is an important but unsolved question which type of training is most effective: to maintain a level representing 90 percent of the maximal oxygen uptake for 40 min, or to tax 100 percent of the oxygen uptake capacity for 16 min" (Åstrand 1986).

Is it more effective to endure a low volume of high-intensity interval training (~ 100% HR_{max}) or a higher volume of low-intensity interval training (~ 90% VO_{2max})? Direct observations demonstrate that world-class athletes may accumulate ~ 15–30 min of work at 95% maximal heart rate (HR_{max}), ~ 40–60 min at 90%, or 60–90 min at 85% of HR_{max} during interval training sessions at these respective intensities (Seiler & Tønnessen, 2009; Seiler, 2010). In contrast to how athletes actually train, several controlled studies comparing the effects of interval or continuous training programs of varying work intensities have matched the interventions for total work, a method typically referred to as *isoenergetic* matching (Eddy et al. 1977; Gorostiaga et al. 1991; Daussin et al. 2007, 2008a, b; Helgerud et al. 2007). That is, training interventions were matched so that the product of duration and intensity for each intervention yielded equivalent total work or caloric expenditure across interventions. In practice, this approach artificially constrains the training so that the overall effort associated with different interval workouts is not equivalent (e.g., it is easier to achieve a target energy expenditure when the interval set requires a lower exercise intensity).

Conceptually, it seems that athletes match their hard interval sessions for overall *effort* and accumulated fatigue, not total *work*. Higher interval training intensity alone is not always the goal of the elite athlete. We have for example observed that internationally elite rowers compared over three decades tended to decrease their training at near VO_{2max} and supra-maximal intensities and increase their volume of interval training at ~ 90% max using longer work periods (Fiskerstrand & Seiler, 2004). Whether the

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intensity distribution characteristics observed among elite endurance athletes training high volumes are also optimal for inducing physiological adaptations in recreational athletes is unclear.

The aim of the present study was to investigate the potential interaction between work intensity and the total work duration in stimulating adaptations to aerobic interval training. We attempted to simulate the typical interval training of athletes by applying an "isoeffort" matching approach when comparing the physiological impact of interval training programs on trained recreational cyclists. Interval prescriptions differed in work period duration (4, 8, or 16 min) and accumulated work duration (16, 32, or 64 min), but were all performed in response to a prescription of "maximal session effort."

Materials and methods

This was a controlled experimental trial involving four groups matched for pre-intervention training characteristics. Groups trained using *only* continuous, low-intensity endurance training (control group), or one of three different high-intensity aerobic interval training programs combined with additional low-intensity training sessions (three interval groups). The training intervention lasted 7 weeks. Physiological test results were compared before and after the intervention period.

Subjects

Thirty-seven recreational cyclists (31 male, 6 female), 25–49 years, were recruited to participate in the study using announcements on the web pages of local cycling clubs. Subject recruitment was mixed gender, based on previous studies demonstrating that the physiological impact of endurance training is not gender specific for this age range (Kohrt et al., 1991; ACSM, 1998; Skinner et al. 2001). Inclusion criteria were: (1) absence of known disease or exercise limitations, based on self-report, (2) 4–10 h/wk training volume, and (3) a goal of competing in local or national cycling competitions. All subjects had experience with interval training before the start of the study and were familiar with training on bicycle ergometers. The study was approved by the human subjects review committee of the Faculty for Health and Sport, University of Agder. All subjects provided informed written consent before participation.

Before preliminary testing, all subjects completed a training questionnaire to estimate the weekly training frequency, the weekly training hours, and the average weekly frequency of interval training during the preceding 2 months. The four training groups were initially matched for (1) weekly training hours and (2) weekly interval training sessions across groups without respect to gender or preliminary test results (Skinner et al. 2001). After randomization to training groups, and allocation of group training times, two subjects requested another group because of time conflicts. They were switched with two subjects initially randomized to the control group such that interval group randomization remained intact.

Thirty-six of 37 subjects completed the study. One subject in the low-intensity training group developed atrial fibrillation 6 weeks into the intervention period and withdrew on the advice of his physician. A second subject from the same group was excluded from the data analysis after it became clear that he had misrepresented his training status at the start of the intervention. The final group sizes were 8 (low intensity) and 9 subjects each in the interval training groups. The pre-intervention physical and training characteristics of these 35 subjects (29 male, 6 female) are presented group-wise in Table 1.

Table 1. Training characteristics at inclusion ($N = 35$)

	Low ($n = 8$)	4 × 16 min ($n = 9$)	4 × 8 min ($n = 9$)	4 × 4 min ($n = 9$)
Age (years)	40 ± 6	43 ± 4	39 ± 8	43 ± 7
Training volume (h/wk)	7.1 ± 2	5.6 ± 2	6.1 ± 3	6.5 ± 2
Interval training (sessions/wk)	1.9 ± 1.0	1.2 ± 0.8	1.4 ± 0.6	1.1 ± 1.0

Values are mean ± SD. Training values are based on the self-reported averages for the 2 months before pre-testing. There were no significant differences among groups for the 3 variables above.

Testing procedures

Preliminary and post-testing was performed over 2 testing days with a minimum of 48 h of recovery. Testing on day 1 consisted of body composition analysis using octapolar impedence (Inbody 720, Biospace Co Ltd., Seoul, South Korea) and a "repeated" continuous incremental test to exhaustion on a bicycle ergometer to determine: (1) peak oxygen consumption (VO_{2peak}), (2) power output at VO_{2peak} ($Power_{VO2peak}$), (3) peak heart rate (HR_{peak}), (4) the first ventilatory turnpoint (VT_1), and (5) the second ventilatory turnpoint (VT_2). Testing on day 2 began with a lactate profile test to identify the workload eliciting 4 mmol/L blood lactate concentration ($Power_{4mM}$). Fifteen minutes after the conclusion of the lactate profile test, subjects performed a time to exhaustion test at 80% of $Power_{VO2peak}$ identified on test day 1 ($TTE_{80\%}$). Specific methods of testing are described below.

All testing was performed on a factory-calibrated Velotron ergometer (Racermate, Seattle, WA, USA). The ergometer was PC controlled and electromagnetically braked. The constant load accuracy of the Velotron is ± 1.3% over a broad workload range (Abbiss et al. 2009). Tests were performed at an ambient temperature between 20 and 22 °C. An electric fan directed at the chest was used to ensure sufficient evaporative cooling. Subjects were instructed to remain seated on the ergometer during testing. Seat height, seat to handlebar distance, and handlebar height were adjusted by each subject as desired. Testing was performed with the ergometer in the pedal frequency-independent workload mode.

Before each test, the Velotron ergometer was calibrated using a roll-down resistance procedure as described by the manufacturer. Calibration was preceded by a 15-min warm-up period to elevate and stabilize the temperature of the interface between the electromagnetic brake and the copper brake plate of the 25 kg flywheel. After warm-up and ergometer calibration, subjects were instrumented for continuous gas exchange and heart rate measurements. They began cycling for 5 min at 60 W before increasing load 20 W/min until voluntary exhaustion or failure to maintain a pedaling rate of 70 rpm. At 60 s post-exhaustion, a blood sample was acquired via finger stick to quantify the peak blood lactate concentration (LactatePro LT-1710, Arkay KDK, Kyoto, Japan). Previous studies from our lab using this ramp protocol with blood sampling at 1, 3, and 5 min have shown that blood lactate measurements acquired 60 s after test termination are a valid measure of peak venous blood lactate (unpublished data).

The test duration was $\sim$ 16–24 min. To ensure that both VO_{2peak} and HR_{peak} were identified, subjects recovered for 7–8 min with very light cycling before completing a second shorter test to exhaustion starting at a higher workload. This second test was started at 50 W below the previous load at exhaustion and maintained for 1 min before increasing progressively by 10–20 W 30 s^{-1} until voluntary exhaustion or failure to maintain $\geq$ 70 rpm. A second blood lactate measurement was taken at the end of this shorter test. The duration of the second exhaustive protocol was typically 3–4 min. Perceived exertion (RPE) was determined at the end of both exhaustive protocols Borg's 6–20 RPE scale (Borg, 1970), based on the perception of overall exertion, after providing subjects with written and verbal instructions regarding its use.

Oxygen consumption was quantified continuously breath by breath using an Oxycon Pro open circuit metabolic cart calibrated before each test (Oxycon, Jaeger BeNeLux Bv, Breda, the Nederlands). Gas sensors and delay time were calibrated via an automated process deriving three gas concentrations using a certified calibration mixture (5.93% CO_2, 15.00% O_2, AGA Gas, Oslo, Norway), room air (20.93% O_2, 0.03% CO_2), and a 50–50 admixture of the test gas and room air. Ventilatory volume was calibrated using a 3 L syringe (Hans Rudolph, Kansas City, MO, USA) at $\sim$ 3 L/s pumping rates. Calibration procedures were repeated for volume and gas sensors until variations between current and previous settings were $<1\%$. We also regularly verified flow rate calibrations at 0.2 and 2.0 L/s using the automatic flow calibration of the Oxycon system. Previous studies have reported high overall validity and measurement stability for the Oxycon Pro system (Rietjens et al. 2001; Carter & Jeukendrup, 2002; Foss & Hallen, 2005). Test–retest reliability in breath by breath modus has been shown to be not significantly different from Douglas bags, $\sim$ 5% (Carter & Jeukendrup, 2002).

Gas exchange was used to quantify VO_2, VCO_2, Ventilatory volume (Ve), respiratory equivalents for O_2 ($VE \cdot VO_2^{-1}$), and CO_2 ($VE \cdot VCO_2^{-1}$). The highest 30 s VO_2 average, 5 s HR average, and blood lactate concentration identified during either exhaustive protocol were defined as VO_{2peak}, HR $_{peak}$, and $Lactate_{peak}$.

Lactate profile changes were used to quantify "threshold" power changes in the present study. However, for comparison with previous studies published in our lab, we also identified VT_1 and VT_2 using changes in EqO_2 and $EqCO_2$ as well as turn-points in the end tidal pressure for O_2 ($PETO_2$) and CO_2 ($PETCO_2$). VT_1 was defined as the point where a break in both EqO_2 and $PETO_2$ was observed without an increase in $EqCO_2$. VT_2 was defined as the point where $EqCO_2$ began to increase, in correspondence with a downward break in PET_{CO2} (Lucia et al. 2000).

On day 2, the lactate profile test began with 10-min warm-up cycling at 50–100 W. The load was then increased to 50 W below the workload at VT_1 identified from test day 1 and maintained for 5 min, followed by blood sampling. Thereafter, the workload was increased 25 W/5 min, with 30-s cycling at 100 W during blood sampling. Testing was terminated when the blood lactate concentration reached $\geq$ 4 mmol/L. The cycling power output eliciting 4 mmol/L blood lactate concentration ($Power_{4\,mM}$) was identified after plotting the power–lactate curve for each subject.

Following a 15-min recovery from the lactate profile test, subjects performed a constant-load ride to quantify the time to exhaustion at 80% of $Power_{VO2peak}$ ($TTE_{80\%}$). This test was performed at the same absolute load before and after the training intervention. During the time-to-exhaustion test, subjects were blinded to elapsed time and heart rate, but were provided vigorous verbal encouragement throughout the test as well as feedback regarding their pedaling frequency if they approached a lower limit of 70 rpm. Blood lactate concentration was measured at 60 s post-exhaustion. Heart rate was measured continuously during all testing (Polar RS400, Kempele, Finland).

Training intervention

Preliminary testing was performed from mid December to early January. The training intervention was performed from mid January to March, corresponding to the early preparation period for these cyclists. Subjects followed one of four training programs over 7 weeks:

- Low-continuous training only at a low to moderate intensity, 4–6 sessions/wk. Training was performed without supervision. Subjects were advised to increase their weekly training volume by 20–30% during the intervention period.
- 4 × 16 – two weekly sessions of 4 × 16 min intervals separated by 3-min recovery periods, in addition to 2–3 additional weekly endurance sessions at a low intensity.
- 4 × 8 – two weekly sessions of 4 × 8 min intervals with 2-min recovery periods, in addition to 2–3 additional weekly endurance sessions at a low intensity.
- 4 × 4 – two weekly sessions of 4 × 4 min intervals with 2-min recovery periods in addition to 2–3 additional weekly endurance sessions at a low intensity.

For all interval prescriptions, subjects were instructed to perform each interval session with their maximal sustainable intensity (*isoeffort*). Interval training sessions were performed in groups on identical Computrainer Lab™ electromagnetically braked ergometers (Racer Mate, Seattle, WA, USA) connected to a central PC running dedicated software. Heart rate and power output were quantified continuously during each work period. RPE was quantified at the end of each work period for every training session. Blood lactate was sampled for each subject during weeks 2, 4, and 6 of the training period. Blood samples were acquired during the third and fourth work periods during interval sessions.

Interval training sessions began with a 15-min warm-up, followed by roll-down resistance determinations as prescribed by the manufacturer to quantify and adjust wheel-ergometer rolling resistance to 2.5–3 lbs. Subjects used their own road racing bicycle connected to the same ergometer during each interval session. Interval training sessions were performed at the same time of the day throughout the intervention period. Room temperature was maintained at 20–22° C for all training sessions. Subjects manipulated cycling load with both gearing and pedal frequency in the same manner as riding on a flat road and were provided feedback regarding their average cycling power in watts at the end of each work interval.

Subjects in the three interval training groups were also instructed to perform all additional endurance training sessions exclusively at a low intensity. Heart rate corresponding to VT_1 was provided to each subject as an intensity guide. All subjects were provided a heart rate watch (RS400 or S610, Polar Elektro Oy, Kempele, Finland) and training diary. For each training session performed (1) training form, (2) duration in minutes, (3) session RPE (Foster, 1998), and (4) heart rate were recorded. Heart rate watches were collected and downloaded weekly. The majority of these additional sessions were also performed on a cycling ergometer due to the winter conditions during the intervention period. Six subjects reported performing a small number of their low-intensity sessions as hiking, jogging, or XC skiing during the 7-week period in order to maintain adequate total training volume during a hard winter when outdoor cycling was not practical.

These subjects were distributed across the different training groups. One subject in the control group performed >25% of his low-intensity training as XC skiing. However, his test results were not different from the control group as a whole before or after the intervention period.

Post-testing

Post-testing was performed over a 10-day period with a randomized order of testing among individuals from the four training groups. To ensure similar pre-testing taper duration in all subjects, some subjects performed one to two additional interval training bouts before testing. Subjects were instructed to treat the week before post-testing as a pre-competition taper week and reduce their training as needed to ensure that they were well rested. They were also advised to reduce the number of interval bouts in their last interval training session from four to two bouts. Post-testing was initiated 72–96 h after the last interval bout for all subjects.

Statistical analysis

Data were analyzed using SPSS 17.0 (SPSS Inc, Chicago, IL, USA) and are presented as mean ± standard deviation. The pre-intervention characteristics of the four training groups were compared using One-Way ANOVA, followed by Tukey's B *post hoc* test if between-group differences were identified. Paired samples *t*-tests were used to compare the pre and post test results in each group. Independent-samples *t*-tests were used to compare the relative change in the physiological variables between males and females. Analysis of Covariance (ANCOVA) was used to estimate 95% confidence intervals for the magnitude of change in (1) VO_{2peak}, (2) $Power_{VO2peak}$, (3) $Power_{4\,mM}$, and (4) $TTE_{80\%}$ among the three interval training groups and compare the training effects. Covariates entered in the ANCOVA were (1) self-reported weekly training hours and (2) weekly frequency of interval training in the 2 months before the intervention period. Confidence intervals (95%) for changes in physiological test variables in the low-intensity control group were calculated without covariate adjustment, given that a reduction in the interval training frequency and a moderate increase in volume were dictated by the training prescription. The frequency distribution of individual response magnitudes across training groups was compared using Chi square. For all comparisons, statistical significance was assumed for $\alpha \leq 0.05$.

Results

The training characteristics averaged over the 7-week intervention period are presented in Table 2. Compared with self-report of training volume before the study, the low and 4 × 16 min groups increased their training volume 20–35% ($P<0.05$) during the intervention period. The weekly training volume remained stable in the 4 × 8 and 4 × 4 min interval training groups.

The 4 × 16, 4 × 8, and 4 × 4 min interval training groups completed 90, 94, and 91% of their 14 scheduled interval sessions, respectively. All subjects performed at least 12 of the 14 scheduled interval sessions. Over 7 weeks, the 4 × 16 min group achieved an average training power output during interval sessions similar to their pre-test power at VT_2 (232 ± 35 vs 231 ± 46 W, 100% VT_2 power). In both 4 × 8 and 4 × 4 min groups, the average interval session power was significantly higher than VT_2 power from preliminary testing (271 ± 22 vs 240 ± 17 W, 113% VT_2 power, and 287 ± 50 vs 218 ± 40 W, 131% VT_2 power, respectively, both $P<0.01$). The different training prescriptions induced three distinct average physiological intensities during training, based on heart rate and

Table 2. Training characteristics of groups during the intervention period

	Low only (6 M, 2F)	4 × 16 min (7 M, 2 F)	4 × 8 min (9 M)	4 × 4 min (7 M, 2 F)
Training freq. (sessions/wk)	4.8 ± 1.2	4.9 ± 1.2	4.6 ± 1.2	4.7 ± 1.2
Interval sessions/wk	–	1.8 ± 0.1	1.9 ± 0.1	1.8 ± 0.1
Training h/wk	8.5 ± 1.5*	7.6 ± 1.9*	5.7 ± 1.5	5.7 ± 2
sRPE low-intensity sessions	3.4 ± 0.2	2.8 ± 0.2	3.4 ± 0.3	3.2 ± 0.2
sRPE interval sessions	–	6.8 ± 0.7	7.3 ± 0.7	7.9 ± 0.8*
Heart Rate (%HR_{peak9})	–	88 ± 2	90 ± 2	94 ± 2**
Blood Lactate (mmol/L)	–	4.9 ± 1.5**	9.6 ± 2.9**	13.2 ± 2.0**
RPE all bouts	–	15.9 ± 0.4	16.4 ± 0.6	18.5 ± 1.2**
RPE last bout		16.9 ± 0.6**	17.6 ± 0.6**	19.1 ± 1.2**

*$P<0.05$ vs other groups.

**$P<0.001$ vs other groups.

sRPE = perceived exertion for the entire training session, average of up to 14 training sessions. RPEall bouts = Borg scale, average value for all interval bouts performed (4 bouts/session 2 sessions/wk × 7 weeks = up to 56 bouts). RPE last bout = Average RPE for the last bout of 14 interval sessions. Blood lactate = average of 3 measurements taken at week 2, 4, and 6 of intervention after third and fourth work periods. Heart rate is based on the average heart rate over the last 25% of each work period.

Table 3. Physiological test results before and after training

	Low ($n=8$)		4 × 16 min ($n=9$)		4 × 8 min ($n=9$)		4 × 4 min ($n=9$)	
	PRE mean (SD)	POST	PRE	POST	PRE	POST	PRE	POST
Weight (kg)	80.4 (12.5)	79.5* (12.2)	83.8 (10.8)	81.6* (11.0)	89.7 (11.3)	88.1* (10.9)	79.9 (13.3)	78.7 (12.9)
Body fat (%)	20.8 (7.2)	20.0* (7.2)	22.2 (5.4)	20.7 (5.2)	20.5 (5.3)	19.5* (6.1)	18.4 (2.9)	17.7 (3.9)
HF_{peak}	182 (12)	182 (9)	183 (9)	178* (8)	185 (7)	180* (8)	179 (7)	177 (8)
$V_{E\ Peak}$(L/min)	157 (35)	159 (40)	155 (35)	158 (39)	168 (19)	180* (21)	149 (35)	159 (37)
Lactate $_{peak}$ (mmol/L)	14.9 (1.6)	13.7* (1.0)	14.8 (1.6)	13.9 (1.5)	14.1 (2.0)	13.4 (1.4)	13.8 (1.5)	14.0 (2.1)
RPE $_{peak}$	19.4 (0.5)	19.5 (0.5)	19.3 (0.7)	19.6 (0.5)	19 (0.7)	19.2 (0.7)	19.4 (0.5)	19.8 (0.3)
VO_{2peak} (L/min)	4.2 (0.7)	4.3 (0.7)	4.3 (0.5)	4.5* (0.7)	4.7 (0.5)	5.1* (0.5)	4.0 (0.8)	4.2 (0.9)
(ml kg/min)	52.7 (8.0)	54.5 (6.9)	51.1 (5.8)	54.4* (5.2)	52.8 (4.8)	58.3* (5.8)	50.4 (5.8)	53.2 (7.6)
Power $_{VO2peak}$								
(W)	349 (44)	358 (48)	361 (51)	372* (50)	378 (52)	410* (27)	343 (68)	361* (72)
(W/kg)	4.5 (0.6)	4.6 (0.6)	4.3 (0.4)	4.6* (0.4)	4.2 (0.5)	4.7* (0.5)	4.3 (0.4)	4.6* (0.5)
$Power_{4\,mM}$ (W)	222 (42)	239* (38)	228 (51)	249* (45)	241 (41)	280* (33)	220 (49)	238* (55)
TTE80% (min)	10.86 (2.6)	12.14 (3.2)	8.52 (1.8)	13.83* (4)	11.88 (4.1)	22.7* (12)	9.7 (2.8)	15.84* (7.1)

*$P<0.05$ vs the pre-test value.

blood lactate responses, with group blood lactate averages during training ranging from ~5 mmol/L in the 4 × 16 min group to ~13 mmol/L in the 4 × 4 min group (Table 2). RPE ratings acquired after each work period over 7 weeks of training were significantly higher in the 4 × 4 min training group, whether averaged over all work periods or only the final work period. RPE ratings showed good repeatability, with the within-subjects SD based on the RPE rating after the fourth bout of each session (i.e. $n = 12$–14 measurements per subject) being ± 1.2 units in the 4 × 16 min group, and only ± 0.6 units in the 4 × 8 and 4 × 4 min groups. Overall session exertion (sRPE) was also significantly higher in the 4 × 4 min group (Table 2).

Physiological test results were similar among the groups before the training intervention (Table 3). All three interval training groups tended to improve in physiological capacity after the training period while the low-intensity group remained relatively unchanged, with the exception of a significant increase in $Power_{4\,mM}$. The 4 × 8 min training group was the only group to show significant improvements in VO_{2peak}, $Power_{VO2\ peak}$, Power $_{4\,mM}$, and $TTE_{80\%}$. Figure 1 presents 95% CIs for the effect magnitude of the different interval training interventions on these four variables. As the figure indicates, the relative change in physiological capacity was the largest for all measures in the 4 × 8 min group. The means (± 95% CIs) for the combined average improvement in VO_{2peak}, Power at VO_{2peak} and Power $_{4\,mM}$ were 4.2 (0.4–8.0), 5.6 (2.1–9.1), 11.4 (8.0–14.9), and 5.5 (2.0–9.0) in LOW, 4 × 16, 4 × 8, and 4 × 4 min groups, respectively ($P<0.02$ for 4 × 8 min vs all other groups). $TTE_{80\%}$ was significantly improved in all three interval training groups, but not in the low-intensity control group (Table 3, Fig. 1). The magnitude of improvement in $TTE_{80\%}$ was significantly correlated with the change in $Power_{4\,mM}$ (Pearsons $r = 0.66$, $P<0.001$). Bodyweight tended to decrease by about 1 kg during the intervention period in all four groups (Table 3). However, this decline was not statistically significant in the 4 × 4 min group.

Because the gender distribution among the four training groups was not identical (no females in 4 × 8 group), we compared the training responses of males and females in the Low, 4 × 16, and 4 × 4 min groups and found that ΔVO_2peak (4 ± 5% vs 3 ± 6%), $\Delta Power_{VO2peak}$ (3 ± 4% vs 3 ± 6%), and $\Delta Power_{4\,mM}$ (7 ± 8% vs 13 ± 8%) were all similar in the 20 male and six female subjects, respectively. Gender differences in adaptive response to training clearly could not explain the relatively greater training response in the 4 × 8 min group.

We also examined the distribution of individual responses to the different training programs. We averaged the relative change in VO_{2peak}, Power-VO_{2peak}, and $Power_{4\,mM}$ for each subject to generate

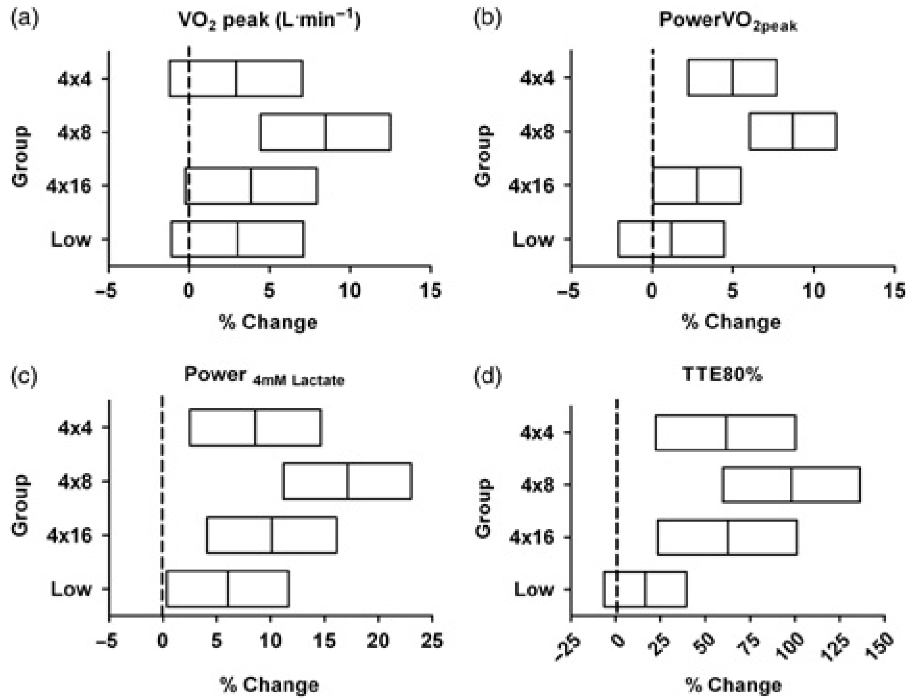

Fig. 1. 95% confidence intervals for relative change in VO_{2peak} (a), power at $VO_{2\ peak}$ (b), power at 4 mmol/L blood lactate concentration (c), and time to exhaustion (TTE) at 80% of power at VO_2peak (d).

a frequency distribution for the overall magnitude of response to training. Based on a range of reported test–retest reliability (CV) values for these parameters of ~ 2–6% (Hopkins et al. 2001) and the overall response distribution observed, we then categorized the averaged training response of each subject as likely to be trivial: <4% average change, moderate: 4–9% improvement, or large: >9% improvement. The distribution of training response was significantly different among the four groups ($P<0.05$, Fig. 2). All subjects in the 4 × 8 min group achieved moderate to large gains in the overall endurance capacity while training responses were more variable in the other interval groups.

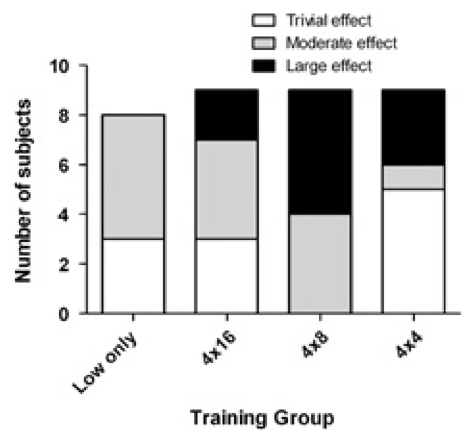

Fig. 2. Distribution of individual response to training by group-averaged change in VO_{2peak} (l/min), power at VO_{2peak} (W), and Power at 4 mM blood lactate concentration (W). Averaged response for each subject was categorized as negative to trivial: <4% improvement, moderate: 4–9% improvement, or large: >9% improvement. The distribution of individual responses was significantly different among the four groups ($P<0.05$).

Discussion

The purpose of this study was to compare the physiological impact of 3, 7-week interval training programs performed at "lactate threshold intensity" "90% intensity", or "VO_2 max intensity" by recreationally trained cyclists. The key finding is that an interval training program where subjects accumulated 32 min of work at $\sim 90\%$ of HR_{max} stimulated moderate to large improvements in both maximal and submaximal performance indicators. This combination of intensity and accumulated duration stimulated more consistent and, on average, larger improvements than twice-weekly interval training of either 4 × 16 min at an approximately maximal lactate steady-state intensity, or 4 × 4 min at intensity eliciting 94% of HR_{max} and ~ 13 mmol/L blood lactate. We also found that the RPE of the interval training programs was more strongly related to work intensity than accumulated duration. Consequently, training 4 × 8 min intervals at slightly reduced heart rate and blood lactate concentration, compared with 4 × 4 min intervals, was associated with significantly lower RPE throughout the 7-week training intervention. Put in the popular vernacular of training investment and reward, cycling 4 × 8 min intervals at 90% HR_{max} yielded the highest *gain for the pain.*

In contrast to several recent interval training studies comparing training interventions matched for total work (*isoenergetic*), we compared interval training programs matched for the prescription of "maximal overall effort" (*isoeffort*). We think this is an important methodological difference for two reasons. First, while isoenergetic matching achieves the goal of isolating intensity as a training variable, *isoeffort* matching of interval training programs is consistent with how athletes typically approach their training. Second, this comparison explores a potentially important integrative signaling effect of intensity and accumulated work duration in inducing adaptive signaling to high-intensity aerobic exercise (Hildebrandt et al., 2003; Laursen PB, 2010).

Based on previous studies in our lab using the same model of interval training prescription (Seiler & Hetlelid, 2005; Seiler & Sjursen, 2004; Seiler et al. 2007) and observations of elite athletes (Seiler & Tønnessen, 2009; Seiler, 2010), we anticipated that the different interval duration prescriptions would constrain work intensity into three reasonably distinct intensity zones. This was confirmed by the significant differences in heart rate and blood lactate concentration observed among the three groups. Blood lactate responses were more clearly distinguishable in the three groups than the HR responses, consistent with the sensitivity of the blood lactate response in this relatively narrow intensity range.

Because we prescribed the same "maximal effort" for each group, independent of interval prescription, it was expected that RPE and session RPE would reach similar values by the end of the training session across groups. This finding, by definition, would have confirmed the successful achievement of "isoeffort" matching. However, despite high motivation and clearly high effort across all three groups, the RPE values demonstrated that the 4 × 4 min prescription elicited significantly higher RPE than 4 × 8 or 4 × 16 min prescriptions. This difference tended to persist when quantified 30 min later as session RPE. It appears that the RPE scale is more sensitive to intensity vs overall "effort", which integrates both intensity and duration. We propose that the current data support a form of "exertional pacing" that integrates the moment to moment perception of intensity with the duration over which that perception must be endured to equal a maximal overall "effort".

All three of the interval training prescriptions elicited greater overall training responses than performing similar or slightly higher total training volumes at a low intensity only. It should be noted, however, that as a group, the Low-intensity training group actually reduced their interval training frequency during the intervention period, as all of the subjects in this group reported performing at least one weekly interval training session before the start of the intervention. Given this, it is noteworthy that their physiological capacity was not significantly affected by the elimination of interval training for 7 weeks. This group did increase their total training volume ~ 20% during the intervention period, which may have helped to prevent a relative detraining effect.

The present results indicate that both intensity and accumulated duration of interval training act in an integrated way to stimulate physiological adaptations. A similar non-linear relationship between intensity of training and 40 km time trial performance change was observed by Stepto et al. (1999), following a 4-week period of training a total of 12 × 30 s at 175% peak power output (PPO), 12 × 60 s at 100% PPO, 12 × 2 min at 90% PPO, 8 × 4 min at 85% PPO, or 4 × 8 min at 80% PPO (Stepto et al. 1999) by well-trained cyclists. Their study only contained three to four subjects per group and the only endurance outcome measure was a 40 km time trial. The present study used larger intervention groups and a more comprehensive evaluation of physiological outcomes. Conceptually, training is often organized into "threshold training" and "VO_2 max training" sessions, with the present 4 × 16 and 4 × 4 min prescriptions being representative. We did not see clear evidence of such adaptive specificity in response to the different training regimes. Intermediate interval intensity between these typical prescriptions induced moderate to large improvements in both maximal oxygen consumption and the lactate-power profile.

Our findings seemingly contradict recent research concluding that "*up to an intensity approximating VO_{2max}, intensity determines the training response, not duration*" (Helgerud et al. 2007). Helgerud and colleagues compared training groups matched for total work, training either 90–95% HR_{max} for 4 × 4 min, lactate threshold training at 85% HR_{max} for 24.25 min, or continuous running at 70% HR_{max} for 45 min. Under these conditions, they observed greater central (cardiovascular) effects at a higher intensity. Our findings are actually consistent with their results when comparing the 4 × 16 with the 4 × 8 min intervals. However, we extended their findings and those of others (Daussin et al. 2007, 2008a, b) by further delineating the interval training prescription. By slightly reducing the work intensity and extending the total duration, recreationally trained subjects working at 90 ± 2% HR_{max} for 32 min achieved greater overall adaptive effects than subjects training for 16 min at 94 ± 2% HR_{max}. Thus, even within a narrow range of exercise intensities (i.e. 85–95% HR_{max}), intensity and work duration appear to be *integrated*, and not *independent* of each other as signaling components of the adaptive response to training.

There was individual variation in the training volume and interval training frequency reported for the 2 months before the study period. Independent of the training group, subjects who reported no weekly interval training ($n = 11$) in the 2 months before study start tended to achieve greater average improvement in VO_{2peak}, $Power_{VO2peak}$, and Power 4_{mM} (9.7%) compared with nine subjects reporting 1–1.5 (4.7%) and 15 subjects reporting two or more interval sessions per week (5.7%, $P = 0.11$ for group comparison). This difference was significant for the increase in VO_{2peak} (8.7 vs 2.1 and 3.6%, respectively, $P < 0.05$). However, randomization of subjects effectively distributed this source of response variation across groups. Further, we used ANCOVA with interval training frequency and training volume included as model covariates in our analysis of group differences in training response. Thus, pre-intervention training status did not explain the greater response magnitude estimates from the 4×8 min group.

The 4×8 min group happened to be composed of nine males, while seven males and two females comprised each of the other interval training groups. As this group improved the most, we investigated whether the gender composition of the groups affected the results. Consistent with previous reports (Kohrt et al. 1991; Medicine, 1998; Skinner et al. 2001), there was no evidence that males responded more robustly to endurance training than females.

We chose to use an open-ended time to exhaustion test (TTE) as an integrated performance measure for comparison among the groups. Previous studies have demonstrated the importance of task familiarization for optimal pacing during performance tests using a fixed distance or duration (Hopkins et al. 2001; Corbett et al. 2009; Foster et al. 2009). Given the testing demands on the subjects, we therefore opted for a TTE test that is not as sensitive to learning effects. TTE measurements have been shown to be less reliable in an absolute sense compared with time trials. However, they elicit large changes in response to interventions, such that overall, they are similarly sensitive to detecting real changes in physiological capacity (Hinckson & Hopkins, 2005).

The testing and training environment was quite competitive among the cyclists, who often knew each other and competed with or against each other in regional cycling races and tours. The same two project administrators were present at all training sessions and gave the same encouragement and power feedback in each group. They also used the same methods in acquiring perceptual and physiological response data throughout the study. Care was also taken to emphasize for the interval groups that the three training programs were considered equivalent in terms of the potential to elicit performance gains both before and during the intervention period.

Physiological and perceptual measures monitored during each training session support that the subjects expended extremely high effort during interval training. Indeed, in the 4×4 group, RPE at the end of the last interval bout during each session approximated RPE_{peak} from pre-testing. Subjects followed the training prescriptions closely. This included performing additional low-intensity training sessions each week such that the total training volume remained essentially constant among the interval groups. The overall training intensity prescription of the three interval groups was polarized, in keeping with observations made of the training characteristics of elite endurance performers in different sports (Seiler, 2010). Anecdotally, subjects from all three interval groups reported that performing two hard sessions per week as prescribed was very demanding and that other training sessions were kept at low-intensity both due to the instructions provided and fatigue.

Post testing was organized to ensure that all subjects had similar and adequate recovery from their last interval training sessions before physiological testing. The subjects were all highly motivated to perform during the post intervention testing. Attention was also paid to instructing the subjects regarding the importance of a mild taper period in the week before post testing to ensure they were all well rested before post testing. Based on the group difference in RPE reported throughout the study by the 4×4 min group, we can speculate that they experienced greater residual fatigue from the training intervention. If this is true, we might also speculate that they would have shown a greater improvement after training had they rested longer than the other two interval groups. While we encouraged all of the study participants to taper their training over the final week as needed to ensure they were well rested, this possibility cannot be excluded. Most interval training studies have not addressed the issue of post-intervention fatigue (e.g. Daussin et al. 2007, 2008a, b; Helgerud et al. 2007).

Perspectives

The results of this study respond to the interval training question raised decades ago by Åstrand and Rodahl (17). They asked whether accumulating 15 min at 100% VO_2 max or accumulating 40 min at 90% VO_2 max elicited greater training effects. We find that when trained cyclists perform a twice-weekly prescription of "maximal effort" interval training, accumulating 32 min at an intensity eliciting $\sim$ 90% HF max is effective in eliciting both a right shift in the blood lactate–power relationship and increased maximal oxygen consumption, as well as a large improvement in time to exhaustion at 80% of pre-intervention peak aerobic power. The 4×8 min prescription induced greater physiological adaptation than both lower and higher intensity intervals programs of 64- and 16-min total duration but was perceived as less stressful than 4×4 min at $\sim 95\%$ HR_{max}. These findings suggest an important interaction between accumulated work duration and work intensity that can be optimized for inducing maximal physiological adaptations at manageable RPE in endurance athletes performing interval training. In these highly motivated but recreationally trained athletes, integrating two hard interval sessions per week into a total training load of four to six sessions per week was very challenging. Their feedback suggests that these prescriptions may represent a reasonable "safe limit" for aerobic interval training prescription in this population.

Key words: intermittent exercise, perceived exertion, lactate threshold, maximal oxygen consumption.

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