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Effects of submaximal and supramaximal interval training on determinants of endurance performance in endurance athletes

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We compared the effects of submaximal and supramaximal cycling interval training on determinants of exercise performance in moderately endurance-trained men. Maximal oxygen consumption (VO_{2max}), peak power output (P_{peak}), and peak and mean anaerobic power were measured before and after 6 weeks (3 sessions/week) of submaximal (85% maximal aerobic power [MP], $HIIT_{85}$, $n = 8$) or supramaximal (115% MP, $HIIT_{115}$, $n = 9$) interval training to exhaustion in moderately endurance-trained men. High-intensity training volume was 47% lower in $HIIT_{115}$ vs $HIIT_{85}$ (304 ± 77 vs 571 ± 200 min; $P < 0.01$). Exercise training was generally associated with increased VO_{2max} ($HIIT_{85}$: +3.3 ± 3.1 mL/kg/min; $HIIT_{115}$: +3.3 ± 3.6 ml/kg/min; Time effect $P = 0.002$; Group effect: $P = 0.95$), P_{peak} ($HIIT_{85}$: +18 ± 9 W; $HIIT_{115}$: +16 ± 27 W; Time effect $P = 0.045$; Group effect: $P = 0.49$), and mean anaerobic power ($HIIT_{85}$: +0.42 ± 0.69 W/kg; $HIIT_{115}$: +0.55 ± 0.65 W/kg; Time effect $P = 0.01$; Group effect: $P = 0.18$). Six weeks of submaximal and supramaximal interval training performed to exhaustion seems to equally improve VO_{2max} and anaerobic power in endurance-trained men, despite half the accumulated time spent at the target intensity.

In endurance sports such as cycling, maximal oxygen consumption (VO_{2max}), endurance capacity, anaerobic fitness, and movement efficiency are important determinants of endurance performance (Joyner & Coyle, 2008). Evidence strongly suggests that both high-volume, low-intensity and low-volume, high-intensity training (Londeree, 1997; Buchheit & Laursen, 2013) are important in order to optimize adaptations in endurance athletes (Stöggl & Sperlich, 2014). High-intensity training, although representing a smaller proportion of athletes' training volume, is a critical component in the training of all successful endurance athletes (Seiler, 2010). High-intensity training is usually performed using interval training, which involves repeated short-to-long bouts of rather high-intensity exercise interspersed with recovery periods (Buchheit & Laursen, 2013). Various high-intensity interval training (HIIT) protocols are utilized in athletes' training programs, including submaximal training (below VO_{2max}), VO_{2max} training, and supramaximal training (superior power output to that produced at VO_{2max}); thus, the optimal exercise training stimulus remains equivocal.

Submaximal interval training can improve endurance performance in highly endurance-trained cyclists (Westgarth-Taylor et al., 1997; Kristoffersen et al., 2014; Stöggl & Sperlich, 2014). Accumulating evidence indicates that supramaximal interval training can also increase maximal aerobic capacity in moderately active adults (Rodas et al., 2000; Gist et al., 2014; Weston et al., 2014), although the beneficial impact of interval training in that intensity domain remains ambiguous in athletic men maintaining usual low-intensity base-training (Weston et al., 2014).

Few studies have directly compared submaximal, maximal, and supramaximal interval training in endurance-trained athletes (Stepto et al., 1999; Laursen et al., 2002; Esfarjani & Laursen, 2007), and those that have report equivocal findings. For example, Stepto et al. (1999) reported greatest improvements in cycling endurance performance following six HIIT sessions over 3 weeks performed at 85% peak power (P_{peak}, i.e., submaximal interval training) and 175% P_{peak} (i.e., supramaximal interval training), compared to HIIT performed at 80%, 90%, or 95% P_{peak}. In contrast, others report that interval training at VO_{2max} performed twice a week for 4 (Laursen et al., 2002) or 10 weeks (Esfarjani & Laursen, 2007) shows larger beneficial effects on performance and key physiological determinants of performance (e.g., VO_{2max} and 3000 m running time) in trained athletes compared to supramaximal interval training at 130% of maximal aerobic speed (Laursen et al., 2002; Esfarjani & Laursen, 2007) and 175% P_{peak} (Laursen et al., 2002; Esfarjani & Laursen, 2007). Furthermore, 6 weeks of supramaximal running interval training (3 sessions/week at 130% 3000-m running speed) provided greater benefits for endurance, sprint, and repeated sprint performance than submaximal interval training (at 3000-m running speed) in physically active but not endurance-trained individuals (Cicioni-Kolsky et al., 2013). Accordingly, whether submaximal or supramaximal interval training elicits the greatest benefits in endurance-trained athletes remains uncertain.

Most studies comparing different training intensities usually match sessions based on achieving the same energy consumption across interventions. However, Seiler et al. (2013) has suggested that matching training regimens on energy consumption induces different overall effort between interval regimens, with total effort or fatigue being lower when energy expenditure is achieved with lower intensity exercise. Importantly, as pointed out by Seiler et al. (2013) and Rønnestad et al. (2015), athletes match their HIIT sessions for overall effort and accumulated fatigue in real life situations, not for total work. Thus, effort matching appears a more valid way to compare intensities, as they would be used in real-world settings.

Therefore, the aim of this study was to assess the impact of effort-matched submaximal and supramaximal interval training on determinants of endurance performance in moderately endurance-trained adults. We hypothesized that, notwithstanding a lower training volume, supramaximal interval training would increase to a greater extent aerobic capacity compared to submaximal interval training. We also expected an improvement in anaerobic capacity following supramaximal, but not submaximal interval training.

Methods

Participants

Nineteen moderately endurance-trained men (27 ± 7 years, 72 ± 10 kg), with a training history of 5 to 12 h/week for at least 2 years, volunteered to participate in this study. Participants were road cyclists (*n* = 9), triathletes (*n* = 7), mountain bikers (*n* = 2), and a cross-country skier, who were training 8.4 ± 2.7 h/week in the month before the study, and were taking part in 0 to 2 interval training sessions/week (0.5 ± 0.7 HIIT sessions/week on average). This study was approved by the local ethics committee and was conducted in accordance to the principles established in the Declaration of Helsinki, with verbal and written informed consent provided by all participants.

Experimental design

Participants reported to the laboratory on four separate occasions over a period of 2 weeks to perform: (a) anthropometric and resting measurements, (b) an incremental cycling test to determine VO_{2max} and P_{peak}, (c) a maximal aerobic power (MP) stepwise intermittent protocol, and (d) a 30-s Wingate test to assess sprint performance (peak and mean anaerobic power). Participants were asked to refrain from training for at least 12 h and to avoid alcohol and caffeine consumption for 24 h before each visit. All sessions were performed in the same order for all participants and there was at least 24 h between testing sessions. After these four preliminary evaluation sessions, participants were matched according to their age and VO_{2max} before one from each pair was randomly assigned to one of two training groups: submaximal ($HIIT_{85}$) or supramaximal ($HIIT_{115}$). By study design, participants in both groups had similar age ($HIIT_{85}$: 26 ± 6 years, $HIIT_{115}$: 27 ± 6 years), height ($HIIT_{85}$: 1.77 ± 0.08, $HIIT_{115}$: 1.78 ± 0.08 m), body mass, % body fat, and VO_{2max} (Tables 1 and 2). The four evaluation sessions were repeated 48–96 h following the end of a 6-week training program (see Fig. 1).

Training interventions

Training consisted of three HIIT sessions per week over a period of 6 weeks, with 48–72 h between sessions. On remaining days, participants were asked to avoid high-intensity exercise, but to maintain a similar low and/or moderate intensity training volume typically performed prior to the study. The $HIIT_{85}$ group performed repeated 1- to 7-min effort bouts, depending on the session, at 85% MP, separated by half the effort time of active recovery (150 W or 50% MP if MP <300 W) until exhaustion. The $HIIT_{115}$ group performed repeated 30-s to 1-min effort bouts, depending on the session, at 115% MP, separated by twice the effort time of active recovery (150 W or 50% MP if MP <300 W) until exhaustion. Table 3 outlines the 18 sessions performed in a randomized order during the 6 weeks by participants from $HIIT_{85}$ and $HIIT_{115}$ groups. The reasons for alternating exercise bout duration from one session to another throughout the 6-week training period in both groups were to reduce monotony of exercise training and to focus on exercise intensity, e.g., 85 vs 115% MP, and not exercise duration. Trainings were performed on Tacx Bushido trainers (Tacx, Terneuzen, The Netherlands).

$HIIT_{85}$ and $HIIT_{115}$ protocols were matched for total effort rather than for total work, which is closer to what athletes typically do when performing hard interval sessions at various intensities (Seiler et al., 2013). Accordingly, a number of repetitions was not specifically prescribed for each participant, but they rather had to keep alternating effort bouts at either 115% or 85% MP and resting periods until exhaustion, defined as the inability to complete an effort bout (Table 3). Session rate of perceived exertion (RPE; 0-10 scale) was obtained within 10 min after the end of each training session (Foster, 1998). After 3 weeks of training, participants' MP

Table 1. Resting measurements pre- and post-training

Group	$HIIT_{85}$ (*n* = 8)		$HIIT_{115}$ (*n* = 9)		*P*-values		
Time	Pre	Post	Pre	Post	Group	Time	Interaction
Body composition							
Body mass (kg)	72.1 ± 12.0	71.7 ± 12.0	73.1 ± 7.5	72.6 ± 7.4	0.84	0.16	0.85
%Body fat (%)	13.4 ± 4.9	12.9 ± 4.0	11.5 ± 5.0	11.6 ± 4.1	0.49	0.65	0.46
Lean mass (kg)	62.4 ± 10.7	62.5 ± 10.9	64.5 ± 5.6	64.0 ± 5.1	0.65	0.60	0.42
Resting hemodynamics							
Systolic blood pressure (mmHg)	115 ± 15	112 ± 10	116 ± 12	124 ± 11	0.27	0.37	0.09
Diastolic blood pressure (mmHg)	66 ± 7	63 ± 6	65 ± 6	71 ± 8	0.31	0.41	0.048*
Heart rate (bpm)	56 ± 8	51 ± 7	54 ± 8	52 ± 6	0.90	0.003	0.10

Values are mean ± SD; $HIIT_{85}$, Submaximal training group; $HIIT_{115}$, Supramaximal training group; *Significant difference ($P < 0.05$) BP, blood pressure.

Table 2. Determinants of endurance performance adaptations to the 6-week HIIT

Group	$HIIT_{85}$ (*n* = 8)		$HIIT_{115}$ (*n* = 9)		*P*-values		
Time	Pre	Post	Pre	Post	Group	Time	Interaction
Incremental exercise protocol							
VT (L/min)	2.06 ± 0.39	2.24 ± 0.55	2.07 ± 0.38	2.17 ± 0.31	0.90	0.03	0.55
RCP (L/min)	3.54 ± 0.53	3.80 ± 0.51	3.48 ± 0.34	3.77 ± 0.42	0.84	0.0001	0.78
P_{peak} (W)	381 ± 46	399 ± 54	397 ± 39	413 ± 35	0.49	0.045	0.87
VO_{2max} (L/min)	3.99 ± 0.63	4.21 ± 0.63	4.01 ± 0.53	4.19 ± 0.40	0.99	0.002	0.75
VO_{2max} (ml/kg/min)	56.0 ± 6.0	59.3 ± 4.7	55.9 ± 4.0	59.2 ± 1.1	0.95	0.002	0.98
HRmax (bpm)	193 ± 6	191 ± 7	188 ± 8	187 ± 6	0.17	0.25	0.80
SBPmax (mmHg)	207 ± 20	205 ± 32	212 ± 33	222 ± 18	0.35	0.54	0.34
DBPmax (mmHg)	81 ± 8	78 ± 6	78 ± 8	68 ± 12	0.11	0.004	0.11
RRmax (breath/min)	49 ± 11	52 ± 9	54 ± 10	54 ± 9	0.40	0.30	0.35
RER	1.39 ± 0.09	1.35 ± 0.10	1.38 ± 0.10	1.42 ± 0.08	0.51	0.87	0.10
MP test							
MP (W)	310 ± 51	315 ± 55	316 ± 44	331 ± 39	0.64	0.04	0.27
T_{MP} (min)	10.3 ± 3.8	13.7 ± 4.1	11.4 ± 4.1	13.5 ± 5.0	0.86	0.002	0.34
Cycling efficiency							
GME (%)	21.5 ± 0.6	20.9 ± 1.0	19.6 ± 1.1	19.4 ± 1.0	0.002	0.06	0.36
Sprint performance							
Peak anaerobic power (W/kg)	15.5 ± 0.8	15.9 ± 1.8	16.6 ± 0.9	16.8 ± 1.2	0.09	0.35	0.66
Mean anaerobic power (W/kg)	10.0 ± 0.5	10.4 ± 0.5	10.3 ± 0.7	10.8 ± 0.5	0.18	0.01	0.70

Values are mean ± SD; $HIIT_{85}$, Submaximal training group; $HIIT_{115}$, Supramaximal training group; VO_{2max}, maximal oxygen consumption, P_{peak}, peak power output during the ramp exercise protocol, HR, heart rate, RER, respiratory exchange ratio, RR, respiration rate, VT, ventilatory threshold, RCP, respiratory compensation point, MP, maximal aerobic power, T_{MP}, time to exhaustion in MP test, GME, gross mechanical efficiency; Significant difference ($P < 0.05$).

was measured, using the same protocol as in the preliminary evaluation, to adjust training intensity for the 3 remaining weeks. Total HIIT volume was calculated for each participant, using the number of repetitions performed and the length of the effort bouts of every session. Work performed was also calculated for each training session. Total work included both effort and recovery bouts, while total HIIT work included only effort bouts. Calculation did not include warm-up and cool down, which were similar between groups.

Methodology

Anthropometric measurements and resting hemodynamics

Stature and body mass were measured in each participant. Lean mass and % body fat were assessed using bioelectrical impedance (InBody520, Biospace, California, USA). Participants then rested supine for 10 min. Heart rate (HR; ECG monitoring) and arterial pressure using photoplethysmography (Wesseling et al., 1993) (Nexfin, Edwards Lifesciences, Ontario, Canada) were continuously monitored on a beat-by-beat basis during the resting period, and the last 5 min of recording was averaged and taken as the baseline.

Maximal oxygen consumption (VO_{2max})

The maximal rate of oxygen consumption (VO_{2max}) was determined using an incremental cycling test performed on an electromagnetically braked upright

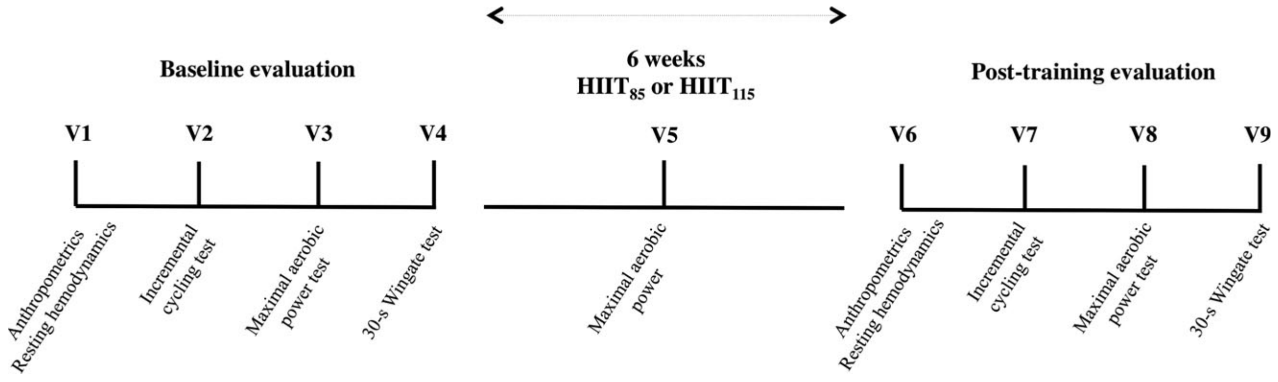

Fig. 1. Experimental design. V, Visit; $HIIT_{85}$, Submaximal training group; $HIIT_{115}$, Supramaximal training group.

cycle ergometer (Corival, Lode, the Netherlands). The test started with 1 min of unloaded pedaling followed by an incremental ramp protocol (30 W/min) to volitional exhaustion. Expired air was continuously recorded using a breath-by-breath gas analyzer (Breezesuite, MedGraphics Corp., Minnesota, Saint Paul, USA) for determination of VO_2, carbon dioxide production (VCO_2), and respiratory exchange ratio (RER: VCO_2/VO_2). Heart rate (HR) was obtained from ECG monitoring and arterial pressure was measured at rest and every 2 min during the test using an automated sphygmomanometer with a headphone circuit option (Model 412, Quinton Instrument, Bothell, Washington, USA). Maximal VO_2 was defined as the highest 30-s averaged VO_2, concurrent with a RER $\geq$1.15. Peak power (i.e., P_{peak}) was the highest power output achieved during the test and maximal HR (HR_{max}), respiratory rate (RR_{max}), and RER (RER_{max}) were defined as the highest values recorded during the test. The ventilatory threshold (VT) was manually determined using the V-slope method (Beaver et al., 1986). The respiratory compensation point (RCP) was determined using the criterion of an increase in ventilatory equivalents for O_2 and CO_2 concomitant to a decrease in end-tidal partial pressure of CO_2 (Wasserman et al., 1999).

Table 3. Interval training sessions that were randomly performed over the 6 weeks by $HIIT_{85}$ and $HIIT_{115}$ participants

$HIIT_{85}$ (n = 8)		$HIIT_{115}$ (n = 9)	
Duration of effort bouts (s)	Duration of recovery bouts (s)	Duration of effort bouts (s)	Duration of recovery bouts (s)
60	30	30	60
60	30	30	60
90	45	30	60
90	45	30	60
120	60	30	60
120	60	40	80
150	75	40	80
150	75	40	80
180	90	40	80
180	90	40	80
240	120	50	100
240	120	50	100
300	150	50	100
300	150	50	100
360	180	60	120
360	180	60	120
420	210	60	120
420	210	60	120

Maximal aerobic power (MP)

Training intensity was set relative to participants' MP in this study. In order to determine the power output of the first stage of the MP test, predicted MP (MP_P) was calculated from the VO_{2max} reached during the incremental cycling test using the following equation:

$$VO_2(\text{mL/min}) = (\text{power output [W]} \times 6\text{kpm/W}) \times 2\text{ml/kpm} + 300\ (\text{ACSM}, 2000)$$

Therefore:

$$MP_P(\text{W}) = (VO_{2max}(\text{mL/min}) - 300)/12$$

Participants performed the MP test on the same cycle ergometer as the incremental cycling test. After a 10-min warm-up (first 5 min: 50% MP_P or 150 W, last 5 min: 5% MP_P or 15 W increase in power output every minute), an intermittent test with 5-min stages was used (see Fig. 2). Cadence was freely chosen throughout the test. MP was defined as the power output of the last completed stage or the power output of an uncompleted stage, where VO_2 increased by >150 mL/min compared to the previous completed stage. The accumulated time of exercise (excluding warm-up and recovery phases) during the MP test (T_{MP}) was used as an index of endurance. VO_2, HR, and arterial pressure were monitored as previously described during the incremental cycling test.

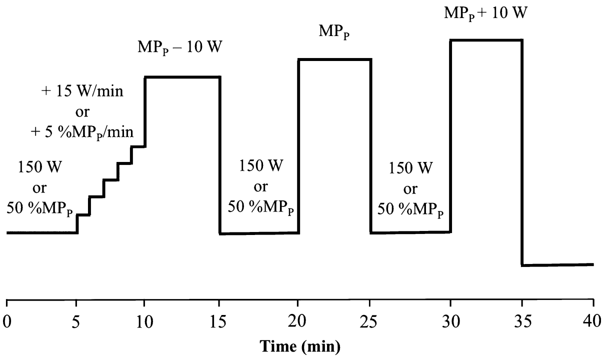

Fig. 2. Maximal aerobic power test protocol. MP_P, predicted maximal aerobic power, during warm-up and recovery phases, cycling intensity is determined relative to MP_P (if $MP_P \leq 300$ W) or in absolute units (if $MP_P > 300$ W).

Cycling efficiency

Gross mechanical efficiency (GME, %) was used to assess cycling efficiency. GME was defined as the ratio of mechanical work output to energy input (Barbeau et al., 1993), where:

$$\text{Mechanical work output (kgm)} = \text{power output (W)} \times \text{time (sec)} \times 0.102\text{kgm/j}$$

and:

$$\text{Energy input (kgm)} = VO_2(\text{L/min}) \times 4.838\text{kcal/L (thermal equivalent)} \times 426.4\text{kgm/kcal}$$

For calculation of GME, data were collected during the fifth min of the warm-up during the MP test.

Sprint performance

Peak and mean anaerobic power were assessed using a 30-s Wingate Anaerobic test. The test was performed on an electronic cycle ergometer (Velotron, RacerMate, Seattle, Washington, USA). Before the test, participants performed a 10-min warm-up at 150 W or 50% MP (for participants with a MP < 300 W) with 5-s non-maximal sprints every min during the last 5 min. Participants were allowed a 2-min resting period before starting the test. The test was preceded by a 2-s unloaded acceleration. The load was then set at 9.4% of participants' body mass, and participants were asked to attain a peak power as quickly as possible and to continue to exercise maximally for the duration of the sprint (30 s), while remaining seated. Peak anaerobic power (peak power/body weight) and mean anaerobic power (mean power/body weight) were calculated.

Statistical analysis

After confirmation of distribution normality using Shapiro–Wilk normality tests, between-group differences (training characteristics) were analyzed using independent samples *t*-tests. For the remaining variables, between-group differences were analyzed using a two-way (Time: Pre vs Post × Group: $HIIT_{85}$ vs $HIIT_{115}$) repeated measures analysis of variance (ANOVA). Following an interaction effect (Time × Group), differences were located using paired (within groups) and independent (between groups) samples *t*-tests, with Bonferroni correction. Significance was established at $P < 0.05$ and data expressed as mean ± standard deviation.

Results

Participant compliance

Data from one participant in $HIIT_{85}$ were removed from analysis due to illness and absence for more than three training sessions. Data from one participant in $HIIT_{115}$ were removed from analysis due to excessive fatigue during the training regime. Therefore, eight participants from $HIIT_{85}$ and nine participants from $HIIT_{115}$ completed the study.

Training characteristics

High-intensity training volume was 47% less in $HIIT_{115}$ than $HIIT_{85}$ (19.3 ± 4.7 vs 36.6 ± 14.4 min/session; $P = 0.005$). Total work performed during each session was 741 ± 317 kJ for $HIIT_{115}$ and 759 ± 200 kJ for $HIIT_{85}$ ($P = 0.89$) when considering effort and recovery bouts, or 585 ± 260 kJ for $HIIT_{115}$ and 421 ± 114 kJ for $HIIT_{85}$ ($P = 0.11$) when considering only effort bouts. Participants from both groups attended an average of 16 ± 1 training sessions during the 6 weeks ($HIIT_{85}$ vs $HIIT_{115}$: $P = 0.79$). Sessions RPE averaged 9.5 ± 0.3 for $HIIT_{85}$ (range: from 8 to 10) and 9.3 ± 0.6 for $HIIT_{115}$ (range: from 5 to 10) ($P = 0.50$).

Anthropometric measurements and resting hemodynamics

Body composition measures were not affected by either HIIT training program (Table 1). Resting HR following both training programs was lowered (interaction, $P = 0.10$; time effect, $P < 0.01$); whereas HIIT training intensity differentially influenced resting DBP and SBP measures, although clear statistical significance was only observed with DBP (Table 1).

Determinants of exercise performance

Incremental cycling exercise to exhaustion

Irrespective of intensity (all interactions, $P > 0.05$), training increased VT, RCP, P_{peak}, and VO_{2max} but decreased maximal DBP (Table 2 and Fig. 3). The other variables measured during the incremental test remained unchanged following training (Table 2).

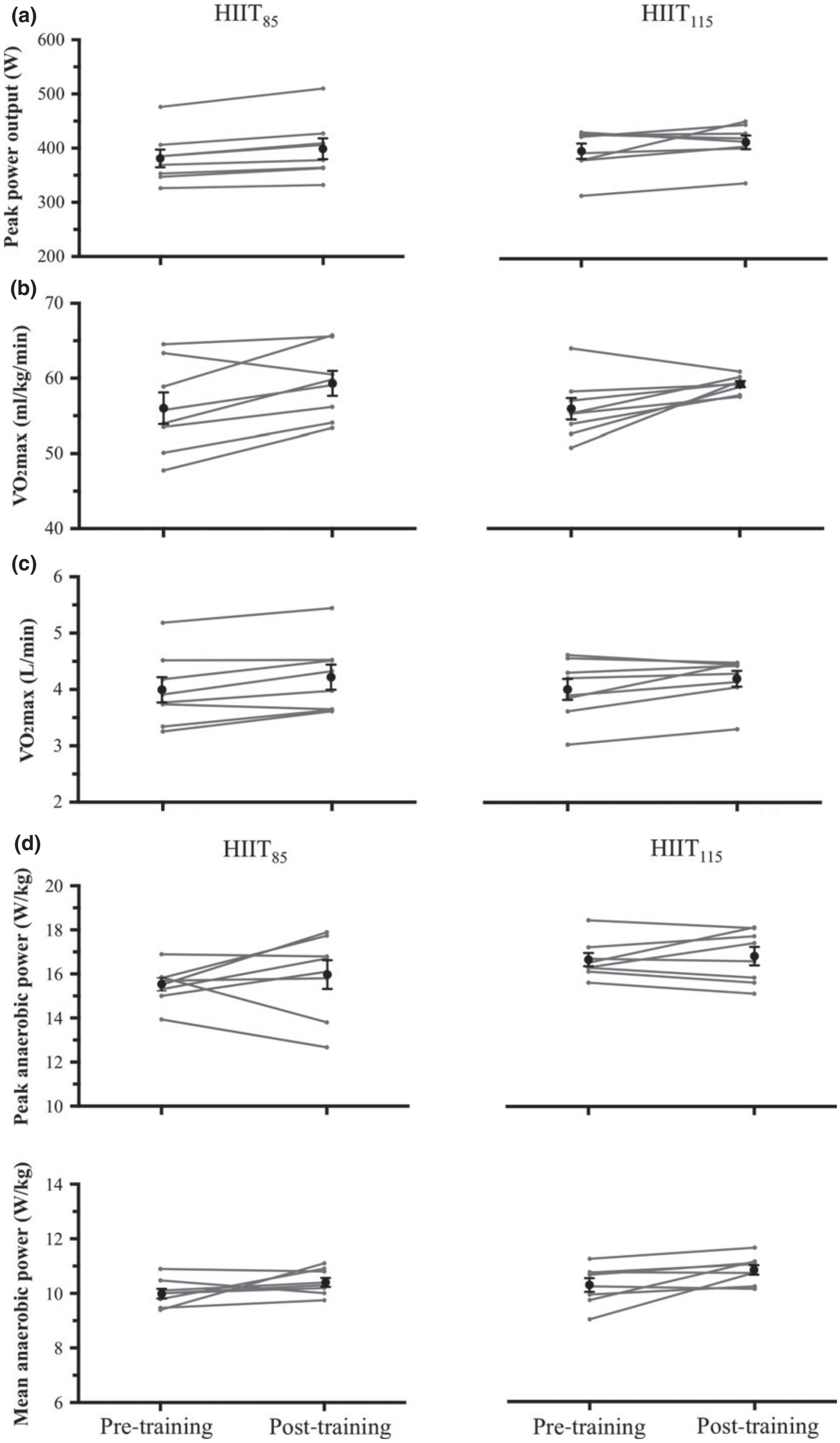

Fig. 3. Individual training responses for peak power output (A) VO_{2max} (B: ml/kg/min; C: L/min) and peak (D) and mean anaerobic power (E) in participants from $HIIT_{85}$ and $HIIT_{115}$ groups. Values are mean ± SEM. VO_{2max}, maximal oxygen consumption.

Mean aerobic power (MP)

Similar increases in MP and T_{MP} were observed following both HIIT training programs (Table 2).

Cycling efficiency

GME for participants in the $HIIT_{85}$ group was higher than the $HIIT_{115}$ group at both pre- and post-training. While on average GME decreased more in the $HIIT_{85}$ than the $HIIT_{115}$ group following training, this did not reach significance (interaction $P = 0.36$) nor did the pooled effect ($P = 0.06$). Mean cadence during GME assessment was similar between evaluation sessions.

Sprint performance

Training increased mean anaerobic power irrespective of training intensity, whereas peak anaerobic power tended to increase following training (Table 2).

Discussion

The primary novel finding associated with the present study was that supramaximal interval training was equally effective compared to effort-matched submaximal interval training given that identical improvements in VO_{2max} and anaerobic power were observed despite half the accumulated time spent at the target intensity.

Submaximal and maximal performance

Results from recent studies suggesting the effectiveness of supramaximal interval training for improving VO_{2max} and submaximal endurance capacity (Rodas et al., 2000; Burgomaster et al., 2005; Gist et al., 2014; Weston et al., 2014) raise the question: is supramaximal HIIT more efficient than submaximal HIIT in improving submaximal and maximal aerobic performance? Our findings suggest that supramaximal HIIT is more time-efficient than submaximal HIIT in improving VO_{2max}, as training at 115% MP for ~19 min/session induced the same improvements in VO_{2max} as training at 85% MP for ~37 min/session, indicating that an increase in training intensity compensates for the decrease in total work duration. These results are supported by those of a recent study (Rønnestad et al., 2015) revealing that 10 weeks of supramaximal interval training (30-s work intervals separated by 15-s recovery for 9.5 min) is superior to effort-matched submaximal interval training (4 × 5 min work intervals separated by 2.5-min recovery periods) of similar total training duration on several endurance and performance measurements in trained cyclists. These results suggest that supramaximal interval training is at least as effective as more traditional submaximal interval training to increase VO_{2max} and endurance performance in moderately trained men.

Supramaximal performance

Improvements in anaerobic fitness have previously been associated with enhancements in endurance performance (Bulbulian et al., 1986; Weston et al., 1997); for example, anaerobic fitness has been found to predict endurance performance in cross-country mountain biking (Inoue et al., 2012), cross-country skiing (Staib et al., 2000), and track endurance cycling (Craig et al., 1993). Findings from the present study indicate that both submaximal and supramaximal HIIT training can be advantageous for endurance athletes as it increases anaerobic fitness (as characterized by mean anaerobic power during a 30-s cycling sprint).

In the present study, HIIT was not associated with an improvement in cycling efficiency. Cycling efficiency is related to endurance performance, as cyclists with a higher efficiency can generate a greater power output for the same VO_2 (Coyle et al., 1992). GME has been reported to be in the range of 18–23% (Coyle et al., 1992), which is in line with our results. Previous studies have shown that HIIT performed at an intensity above onset of blood lactate accumulation (Hopker et al., 2010) and strength training (Sunde et al., 2010) can slightly improve cycling efficiency in competitive cyclists. Freely chosen cadence and accumulated fatigue after the training protocol may explain our results, as both cadence and fatigue alter GME (Chavarren & Calbet, 1999; Millet et al., 2000).

There are some limitations to our study that need to be addressed. Without a performance test (i.e., a time-trial) it is difficult to state which of the two training interventions will further improve endurance performance. However, the aim of the present study was to assess the impact of the two training intensities on important determinants of endurance performance and not performance *per se*. Furthermore, our participants were moderately endurance-trained men and therefore our results cannot necessarily be extended to women, healthy or diseased, or high-performance athletes. We also acknowledge that the small sample size of our study is associated with interpretive limitations, although a retrospective power analysis revealed that we were adequately powered to detect main effects with values exceeding 0.8 at $P < 0.05$ for the main determinants of exercise performance examined in this study.

In summary, these findings suggest that both submaximal and supramaximal interval training, performed to exhaustion three times a week for 6 weeks, can equally improve VO_{2max} and anaerobic power in endurance-trained men despite half the accumulated time spent at the target intensity. These results may alternatively imply that submaximal interval training is just as effective as supramaximal training to enhance these physiological indices of performance, while avoiding both physiological and psychological stress that accompany supramaximal training programs.

Perspectives

The results of this study provide an answer to a question raised by the growing interest of researchers, coaches, and athletes toward supramaximal interval training: Is effort-matched submaximal and supramaximal interval training equally efficient in improving determinants of endurance performance in endurance-trained men? It appears that both submaximal and supramaximal interval training, performed to exhaustion three times a week for 6 weeks, can equally improve VO_{2max} and anaerobic power in these moderately trained athletes. Further research is needed to assess the impact of long-term submaximal and supramaximal training as well as the effect of combining both types of training in the same period or in consecutive training blocks on endurance performance.

Key words: Aerobic capacity, sprint performance, endurance training, cycling.

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References

ACSM. ACMS's guidelines for exercise testing and prescription. 6 ed. Michigan: American College of Sports Medicine Series, 2000: 368.

Barbeau P, Serresse O, Boulay MR. Using maximal and submaximal aerobic variables to monitor elite cyclists during a season. Med Sci Sports Exerc 1993: 25(9): 1062–1069.

Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol 1986: 60(6): 2020–2027.

Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. Sports Med 2013: 43(5): 313–338.

Bulbulian R, Wilcox AR, Darabos BL. Anaerobic contribution to distance running performance of trained cross-country athletes. Med Sci Sports Exerc 1986: 18(1): 107–113.

Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, Gibala MJ. Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. J Appl Physiol 2005: 98(6): 1985–1990.

Chavarren J, Calbet JAL. Cycling efficiency and pedalling frequency in road cyclists. Eur J Appl Physiol 1999: 80(6): 555–563.

Cicioni-Kolsky D, Lorenzen C, Williams MD, Kemp JG. Endurance and sprint benefits of high-intensity and supramaximal interval training. Eur J Sport Sci 2013: 13(3): 304–311.

Coyle EF, Sidossis LS, Horowitz JF, Beltz JD. Cycling efficiency is related to the percentage of type I muscle fibers. Med Sci Sports Exerc 1992: 24 (7): 782–788.

Craig NP, Norton KI, Bourdon PC, Woolford SM, Stanef T, Squires B, Olds TS, Conyers RAJ, Walsh CBV. Aerobic and anaerobic indices contributing to track endurance cycling performance. Eur J Appl Physiol Occup Physiol 1993: 67(2): 150–158.

Esfarjani F, Laursen PB. Manipulating high-intensity interval training: effects on VO_{2max}, the lactate threshold and 3000 m running performance in moderately trained males. J Sci Med Sport 2007: 10(1): 27–35.

Foster C. Monitoring training in athletes with reference to overtraining syndrome. Med Sci Sports Exerc 1998: 30(7): 1164–1168.

Gist NH, Fedewa MV, Dishman RK, Cureton KJ. Sprint interval training effects on aerobic capacity: a systematic review and meta-analysis. Sports Med 2014: 44(2): 269–279.

Hopker J, Coleman D, Passfield L, Wiles J. The effect of training volume and intensity on competitive cyclists' efficiency. Appl Physiol Nutr Metab 2010: 35(1): 17–22.

Inoue A, Filho AS, Mello FC, Santos TM. Relationship between anaerobic cycling tests and mountain bike cross-country performance. J Strenght Cond Res 2012: 26(6): 1589–1593.

Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. J Physiol 2008: 586(1): 35–44.

Kristoffersen M, Gundersen H, Leirdal S, Iversen VV. Low cadence interval training at moderate intensity does not improve cycling performance in highly trained veteran cyclists. Front Physiol 2014: 5: 34.

Laursen PB, Shing CM, Peake JM, Coombes JS, Jenkins DG. Interval training program optimization in highly trained endurance cyclists. Med Sci Sports Exerc 2002: 34(11): 1801–1807.

Londeree BR. Effect of training on lactate/ventilatory thresholds: a meta-analysis. Med Sci Sports Exerc 1997: 29(6): 837–843.

Millet G, Lepers R, Lattier G, Martin V, Babault R, Maffiuletti N. Influence of ultra-long-term fatigue on the oxygen cost of two types of locomotion. Eur J Appl Physiol 2000: 83(4–5): 376–380.

Rodas G, Ventura JL, Cadefau J, Cussó R, Parra J. A short training programme for the rapid improvement of both aerobic and anaerobic metabolism. Eur J Appl Physiol 2000: 82(5–6): 480–486.

Rønnestad BR, Hansen J, Vegge G, Tønnessen E, Slettalokken G. Short intervals induce superior training adaptations compared with long intervals in cyclists – an effort-matched approach. Scand J Med Sci Sports 2015: 25: 143–151.

Seiler S. What is best practice for training intensity and duration distribution in endurance athletes? Int J Sports Physiol Perform 2010: 5 (3): 276–291.

Seiler S, Jøranson K, Olesen ND, Hetlelid KJ. Adaptations to aerobic interval training: interactive effects of exercise intensity and total work duration. Scand J Med Sci Sports 2013: 23: 74–83.

Staib JL, Im J, Caldwell Z, Rundell KW. Cross-country ski racing performance predicted by aerobic and anaerobic double poling power. J Strenght Cond Res 2000: 14(3): 282–288.

Stepto NK, Hawley JA, Dennis SC, Hopkins WG. Effects of different interval-training programs on cycling time-trial performance. Med Sci Sports Exerc 1999: 31(5): 736–741.

Stöggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Front Physiol 2014: 5: 33.

Sunde A, Støren O, Bjerkaas M, Larsen MH, Hoff J, Helgerud J. Maximal strenght training improves cycling economy in competitive cyclists. J Strenght Cond Res 2010: 24(8): 2157–2165.

Wasserman K, Hansen JE, Sue DY, Casaburi R, Whipp BJ. Physiology of exercise. In: Principles of exercise testing and interpretation. 3rd edn. Philadelphia: Lippincott Williams & Wilkins, 1999: 30–32.

Wesseling KH, Jansen JRC, Settels JJ, Schreuder JJ. Computation of aortic flow from pressure in humans using a non-linear, three-element model. J Appl Physiol 1993: 74(5): 2566–2573.

Westgarth-Taylor C, Hawley JA, Ricard MD, Myburgh KH, Noakes TD, Dennis SC. Metabolic and performance adaptations to interval training in endurance-trained cyclists. Eur J Appl Physiol 1997: 75(4): 298–304.

Weston AR, Myburgh KH, Lindsay FH, Dennis SC, Noakes TD, Hawley JA. Skeletal muscle buffering capacity and endurance performance after high-intensity interval training by well-trained cyclists. Eur J Physiol Occup Physiol 1997: 75(1): 7–13.

Weston M, Taylor KL, Batterham AM, Hopkins WG. Effects of low-volume high-intensity interval training (HIT) on fitness in adults: a meta-analysis of controlled and non-controlled trials. Sports Med 2014: 44(7): 1005–1017.