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# Short intervals induce superior training adaptations compared with long intervals in cyclists – An effort-matched approach

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The purpose of this study was to compare the effects of 10 weeks of effort-matched short intervals (SI; n = 9) or long intervals (LI; n = 7) in cyclists. The high-intensity interval sessions (HIT) were performed twice a week interspersed with low-intensity training. There were no differences between groups at pretest. There were no differences between groups in total volume of both HIT and low-intensity training. The SI group achieved a larger relative improvement in VO<sub>2max</sub> than the LI group (8.7% ± 5.0% vs 2.6% ± 5.2%), respectively,  $P \le 0.05$ ).

For well-trained endurance athletes to achieve optimal training stimulus, it is recommended that a certain amount of training is conducted at intensities of 90-100% of maximal oxygen uptake (VO<sub>2max</sub>; Wenger and Bell 1986; Laursen and Jenkins 2002). However, continuous work at such high intensities cannot be sustained for prolonged periods of time, thus limiting total training time at this intensity during a single training session. The total accumulated time of work at this high intensity during a single session can be increased using various modes of interval programs (MacDougall & Sale, 1981). For a long time, it has been recognized that high-intensity training (HIT) can improve endurance performance (e.g., Shephard, 1968; Fox et al., 1973). HIT can roughly be divided into longer work intervals of ~3-5 min at relatively high exercise intensity (LI) or shorter work intervals (SI) of ~15-45 s at even higher exercise intensity than used during the longer intervals (Tschakert & Hofmann, 2013). Different work over recovery ratios have been used, with 2:1 and 1:1 as the most frequently reported ratio (reviewed in Midgley & McNaughton, 2006; Rozenek et al., 2007).

Both SI (Tabata et al., 1996; Iaia et al., 2008; Gunnarsson & Bangsbo, 2012) and LI (Lindsay et al., 1996; Westgarth-Taylor et al., 1997; Rønnestad et al., 2012) have improved endurance performance or performance-related measurements in endurance-trained participants. Furthermore, the few studies that have Mean effect size (ES) of the relative improvement in all measured parameters, including performance measured as mean power output during 30-s all-out, 5-min all-out, and 40-min all-out tests revealed a moderate-to-large effect of SI training vs LI training (ES range was 0.86–1.54). These results suggest that the present SI protocol induces superior training adaptations on both the high-power region and lower power region of cyclists' power profile compared with the present LI protocol.

investigated the training effects of both SI and LI in endurance-trained participants report similar improvements with the two HIT protocols (Stepto et al., 1999; Laursen et al., 2005; Helgerud et al., 2007). However, methodological issues such as small sample size, short intervention period, and/or matching training regimens on total energy expenditure makes it somewhat difficult to compare the results. It has been suggested that matching training regimens on energy consumption artificially induces different overall effort between different interval regimens (Seiler et al., 2013). The performance effects of effort-matched SI and LI in cyclists remain, to the best of our knowledge, to be investigated. It has been suggested that the training time  $\ge 90\%$  VO<sub>2max</sub> could serve as good criteria to judge the effectiveness of the stimulus to improve aerobic fitness (Thevenet et al., 2007). In a recent study, we found that a SI session alternating between 30-s work interval and 15-s recovery until exhaustion induced a longer total time above 90% of VO<sub>2max</sub> than a LI session with work intervals of ~4.5 min separated by recovery periods lasting 50% of the work period until exhaustion (Rønnestad & Hansen, 2013). However, the intensity in both sessions was the minimal power that theoretically elicits VO<sub>2max</sub> (PVO<sub>2max</sub>) and might not reflect real-world practice. Furthermore, it is difficult to know whether there would be differences in long-term training adaptations between the SI and LI protocol.

Therefore, the primary aim of the present study was to investigate the training adaptations to 10 weeks of effortmatched SI or LI in cyclists. In order to get a picture of the effects of these two training regimes on both the high- and lower power part of a cyclist's power profile, both short-duration and long-duration performance, as well as classical indicators of endurance performance, were investigated. We hypothesized that SI would provide superior effects on both the high- and lower power part of a cyclist's power profile.

#### Methods

#### Subjects

Twenty male competitive cyclists volunteered for the study. Based on the peak power output, power to weight ratios, and average amount of training hours per week, the cyclists were regarded as trained to well trained (Jeukendrup et al., 2000). The cyclists (age =  $33 \pm 10$  years, height =  $182 \pm 4$  cm, body mass =  $76 \pm 6$  kg) were randomly allocated to a SI group or a LI group. The randomization was stratified by VO<sub>2max</sub>. Two cyclists from the LI group did not complete the study because of illness whereas one cyclist from each of the groups withdraws from the study without giving a reason, resulting in nine cyclists in the SI group and seven cyclists in the LI group. During the 4 weeks prior to the intervention period, the cyclists were free to perform what kind of

Table 1. Duration (in hours per week) of the endurance training performed during the 10-week intervention period in the group that performed short intervals (SI) and the group that performed long intervals (LI)

Intensity zone	SI ( <i>n</i> = 9)	LI ( <i>n</i> = 7)
Intensity zone I (60–82% of HR <sub>max</sub> ) Intensity zone II (83–87% of HR <sub>max</sub> ) Intensity zone III (88–100% of HR <sub>max</sub> )	$\begin{array}{c} 7.8 \pm 5.9 \\ 0.6 \pm 0.2 \\ 0.7 \pm 0.3 \end{array}$	$\begin{array}{c} 9.7\pm 3.5\\ 0.7\pm 0.4\\ 0.6\pm 0.3\end{array}$

Values are mean  $\pm$  standard deviation.  $\ensuremath{\mathsf{HR}_{\mathsf{max}}}$  , maximal heart rate.

Table 2. Characteristics of the short-interval (SI) and long-interval (LI) protocols used during the intervention

training they wanted. There were no significant differences between the SI group and the LI group in training hours during the 4-week period prior to pretest ( $8 \pm 5$  and  $10 \pm 5$  h training per week, respectively, P = 0.6). The majority of this training was low-intensity endurance training, but  $0.3 \pm 0.2$  and  $0.4 \pm 0.3$  h per week, respectively, was HIT. The study was performed according to the ethical standards established by the Helsinki Declaration of 1975 and was approved by the local ethical committee at Lillehammer University College. All cyclists signed an informed consent form prior to participation.

#### Training intervention

There was no difference between groups in total training duration or in duration in the different training intensity zones (Table 1). The endurance training was divided into three heart rate (HR) zones: (a) 60-82%, (b) 83-87%, and (c) 88-100% of maximal HR and reported in a training diary. The SI group performed 30-s work intervals separated by 15-s recovery periods continuously for 9.5 min followed by 3-min recovery period. This 9.5-min period was performed three times in one interval session for the SI group. The LI group performed  $4 \times 5$ -min work intervals separate by 2.5-min recovery periods. Thus, the total time of work intervals in one interval session for the SI and LI was 19.5 and 20.0 min, respectively, whereas the total recovery period was 9.0 and 7.5 min, respectively (Table 2). For both groups, power output during the recovery periods was 50% of the power output used during work intervals. Rate of perceived exertion (RPE) was recorded after each interval series using Borg's 6-20 scale (Borg, 1982), and session RPE (Foster, 1998) was obtained 30 min after each interval session. Venous blood samples from the fingertip were analyzed for lactate concentration ([La<sup>-</sup>]) after each interval series during the first training week, and thereafter at least every third week. All measurements of [La-] during both training and testing in the present study were performed with the same portable instrument (Lactate Pro LT-1710, Arkray, Inc., Kyoto, Japan). All sessions during the first training week and at least one session every third week in both groups were supervised, and strong verbal encouragement was given by the investigators. Both groups were instructed to perform intervals at their maximal sustainable work intensity, aiming to achieve the highest possible average power output during each interval session. This makes the actual mean

	SI ( <i>n</i> = 9)	LI ( <i>n</i> = 7)
Duration of work intervals (s)	30	300
Relief duration per series (s)	15	0
Number of work intervals per series	13	1
Total work period per series (s)	13 × 30 s = 390	1 × 300 s = 300
Total relief period per series (s)	12 × 15 s = 180	0
Number of series	3	4
Time between series (s)	180	150
Total work period per session (s)	3 × 390 = 1170	4 × 300 = 1200
Total recovery period per session (s)	$(3 \times 180 \text{ s}) + (2 \times 180 \text{ s}) = 900$	3 × 150 = 450
Intensity during relief/recovery phases	50% of work interval	50% of work interval
Total session time (exclusive warm-up/-down) (s)	1170 + 900 = 2070	1200 + 450 = 1650
Power output during work intervals (W)	$363 \pm 32^{\#}$	$324 \pm 42$
[La-] across all work series (mmol/L)	$10.6 \pm 2.5$	$10.0 \pm 3.5$
[La <sup>-</sup> ] after last work interval (mmol/L)	$11.4 \pm 2.4$	$10.5 \pm 3.7$
RPE across all work series	$17.8 \pm 0.5$	$17.6 \pm 0.8$
RPE last work series	$18.5 \pm 0.4$	$18.2 \pm 0.4$
Session RPE	$7.8\pm0.5$	$7.5 \pm 1.1$

<sup>#</sup>Larger than LI (P < 0.05).

Values are mean  $\pm$  standard deviation.

RPE, rate of perceived exertion.

power output of each interval session an indicator of performance level. Similar effort during both the SI and LI training was evident with no difference between groups in [La<sup>-</sup>], RPE, or session RPE during the interval sessions (Table 2). Despite these evidence for similar efforts between groups, it may be noted a small, nonstatistical significant, and decreased response in the LI group between week 3–4 and 5–6 (Fig. 1). It must be noted that when the duration of work intervals differs as much as in the present investigation and total work time is similar, there will be differences between groups in power output and thus total energy expenditure during the HIT sessions, despite similar effort in the two groups. That being said, similar effort seems to be closer to how athletes typically perform their training (Seiler et al., 2013).

Each interval session started with an individual 15-20-min warm-up that was concluded by two to three submaximal sprints lasting 20-30 s. This room for individual optimizing of the warm-up was given because of different preferences among cyclists. SI and LI training were performed either on the cyclists' own bikes equipped with a power meter (PowerTap SL 2.4, CycleOps, Madison, WI, USA) mounted on the rear wheel and connected to a roller or on an advanced cycle ergometer (Lode Excalibur Sport, Lode B.V., Groningen, The Netherlands). Four cyclists in the SI group performed all their training on private bikes, and to ensure rapid increase and decrease in power output during the SI sessions, they mounted the bike on an electromagnetically braked roller (CompuTrainer Lab<sup>TM</sup>, RacerMate, Inc., Seattle, WA, USA). The remaining five cyclists in the SI group performed their HIT sessions on the Lode test ergometer. All other training was performed on their own bike. In theory, training on the test ergometer could lead to a larger improvement at the posttest due to improved familiarization. However, all cyclists participating in the present study had previous experience with the test ergometer before intervention start, and the ergometer is extremely precise in its possibilities to adjust seating, handle position, crank arm length, and the exact seating position of each rider was saved on the ergometer computer ensuring identical and optimal seating position of each individual rider. All these factors, and the fact that cycling is a rather coordinative easy movement and the cyclists were well trained, contribute to minimize any potential familiarization advantages with performing the HIT sessions on it. This is underlined by the finding of similar improvements in 40-min all-out performance between the subgroup performing HIT sessions on the ergometer and on own bike (11% and 13% improvements, respectively). The individual SI sessions were programmed in the roller and cycle ergometer software. The power output during the first short work intervals was set to PVO<sub>2max</sub>. A previous study from our laboratory indicates that



*Fig. 1.* Mean power output during the short-interval sessions (SI) and long-interval sessions (LI) across the 10-week intervention period. \*Larger than week 1-2 (P < 0.05). \*Larger relative increase than the LI group (P < 0.05).

#### Short intervals vs long intervals

PVO<sub>2max</sub> is a suitable intensity for the work intervals used in the SI group (Rønnestad & Hansen, 2013). The power output during the subsequent work intervals during the intervention period was individually adjusted between each interval series to ensure optimal individual power output (i.e., highest possible average power output during each session). The intervention was completed during the cyclists' early preparation phase.

#### Testing procedures

Physical tests were performed before and after the 10-week intervention period. The cyclists were instructed to refrain from all types of intense exercise the day preceding each of the three test days. They were also instructed to consume the same type of meal before each test and were not allowed to eat during the hour preceding a test or to consume coffee or other products containing caffeine during the 3 h preceding the tests. All tests were performed under similar environmental conditions (18-21 °C), with a fan ensuring circulating air around the cyclist. Strong verbal encouragement was given during all tests to ensure maximal effort. All tests for the individual cyclists were conducted at the same time of day  $(\pm 1 h)$  to avoid any influence of circadian rhythm. All testing was performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode B.V.), which was adjusted according to each cyclist's preference for seat height, horizontal distance between tip of seat and bottom bracket, and handlebar position. Identical seating positions were used for all tests.

Blood lactate profile test, VO<sub>2max</sub>, and PVO<sub>2max</sub>

The first test day included a blood lactate profile and a VO<sub>2max</sub> test. The blood lactate profile has been described elsewhere (Rønnestad et al., 2010). Briefly, the test started without warm-up, with 5-min cycling at 125 W. Cycling continued and power output was increased by 50 W every 5 min. Blood samples were taken from a fingertip at the end of each 5 min bout and were analyzed for whole blood [La-]. The test was terminated when a [La-] of 4 mmol/L or higher was measured. VO<sub>2</sub>, respiratory exchange ratio (RER), and HR were measured during the last 3 min of each bout. HR was measured using a Polar S610i HR monitor (Polar, Kempele, Finland). VO2 was measured (30-s sampling time) using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). The gas analyzers were calibrated with certified calibration gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger) was calibrated before every test with a 3-L, 5530 series, calibration syringe (Hans Rudolph, Kansas City, MO, USA). The same metabolic system with identical calibration routines was used on all subsequent tests. From this continuous incremental cycling test, power output at lactate threshold was calculated as the power output that corresponded with 4 mmol/L. Cycling economy was calculated as the average oxygen consumption between 3.0 and 4.5 min of the first three 5-min submaximal stages of the blood lactate profile test (125, 175, and 225 W). Gross efficiency was calculated using the same method as Coyle et al. (1992). Briefly, rate of energy expenditure was calculated using gross VO2 values and their matching RER values, and gross efficiency was expressed as the ratio of work accomplished per minute to caloric expenditure per minute.

After termination of the blood lactate profile test, the cyclists had 15 min of recovery cycling before completing another incremental cycling test for determination of  $VO_{2max}$ . This test has been described elsewhere (Rønnestad et al., 2011). Briefly, the test was initiated with 1 min of cycling at a power output corresponding to 3 W/kg (rounded down to the nearest 50 W). Power output was subsequently increased by 25 W every minute until exhaustion.  $VO_{2max}$  was calculated as the average of the two highest 30-s  $VO_2$ 

measurements. HR  $\geq$  95% of the subjects reported maximal HR, RER  $\geq$  1.05, and [La<sup>-</sup>]  $\geq$  8.0 mmol/L were required as criteria to evaluate if VO<sub>2max</sub> was obtained. Peak aerobic power output (W<sub>max</sub>) was calculated as the mean power output during the last 2 min of the incremental VO<sub>2max</sub> test. PVO<sub>2max</sub> was calculated according to the description of Daniels et al. (1984). This method calculates PVO<sub>2max</sub> by extrapolation of the individual VO<sub>2</sub> to submaximal power output relationships to the measured VO<sub>2max</sub>, and has previously been used to determine PVO<sub>2max</sub> in well-trained cyclists (Rønnestad, 2013).

#### Wingate test and 5-min all-out trial

Both the 30-s Wingate test and the 5-min all-out trial were performed on a cycle ergometer on the second test day. Braking resistance was set to 0.8 Nm/kg body mass. After a 20-min warm-up (including two to three submaximal sprints and a 1-min rest), the cyclists started cycling at 60 rpm without braking resistance. Then, following a 3-s countdown, the braking resistance was applied to the flywheel and remained constant throughout the 30-s all-out test. Mean power output was presented as the average power output sustained throughout the 30 s. Cyclists remained seated throughout the test, and strong verbal encouragement was provided throughout. Cyclists were instructed to pedal as fast as possible from the start and not to conserve energy for the last part of the test. Cyclists then recovered by cycling at ~100 W for 15 min before the 5-min all-out trial. The cyclists were instructed to cycle at as high average power output as possible during the 5-min trial and to remain seated during the entire test. The cyclists were allowed to adjust the power output throughout the trial using an external control unit mounted on the handlebar. Performance during the 5-min all-out test was measured as the average power output. Such closed-end tests have been shown to have a low coefficient of variation in trained cyclists (CV < 3.5%; Foss & Hallén, 2005).

#### Forty-min all-out trial

The 40-min all-out trial was performed on the third test day and started after a 15-min individual warm-up, which was concluded by two to three submaximal sprints. This small room for individual optimizing of the warm-up was given due to different preferences among the cyclist. During the 40-min trial, the cyclists were instructed to cycle at as high average power output as possible. Performance was measured as the average power output during the trial. The cyclists were allowed to adjust the power output throughout the trial using an external control unit mounted on the handlebar. The cyclists received no feedback about HR and cadence, but they were aware of remaining time and instantaneous power output. The cyclists were allowed to occasionally stand in the pedals during the trial and to drink water ad libitum. At the posttest, [La-] was measured every 5th min, and mean values for the first 20 min and last 20 min was compared between the groups. Unfortunately, because of technical problems [La-] was not measured every 5th min at pretest.

#### Statistical analyses

All values presented in the text, figures, and tables are mean  $\pm$  standard deviation. To test for differences between groups at baseline and training volume, unpaired Students *t*-tests were used. Because of the small sample size and expectations of small changes in these already well-trained cyclists, the data were analyzed with *t*-tests and mean effect size (ES). ES was calculated as Cohen's *d* to compare the practical significance of the performance improvements among the two groups. The criteria to interpret the magnitude of the ES were 0.0–0.2 trivial, 0.2–0.6 small,

0.6-1.2 moderate, 1.2-2.0 large, and > 2.0 very large (Hopkins et al., 2009). Pre- to post-intervention within group differences were compared using paired Students t-test (VO<sub>2max</sub>, W<sub>max</sub>, power output during 30 s, 5- and 40-min tests, and at 4 mmol/L [La-]). To test for any differences in relative changes between the groups, unpaired Students t-tests were performed. For each group, mean power output during the work intervals for every 2-week period was compared using one-way repeated measures analysis of variance (ANOVA). If the ANOVA reached significance, a Tukey's honestly significant difference test was performed for post-hoc analysis. To test for differences between groups in changes in mean power output during each 2-week period, two-way repeated measures ANOVA (time and group as factors) with Bonferroni post-hoc tests were performed. t-tests were performed in Excel 2010 (Microsoft Corporation, Redmond, WA, USA). ANOVA analyses were performed in GraphPad (GraphPad Software, Inc., San Diego, CA, USA). All analyses resulting in  $P \le 0.05$  were considered statistically significant. P-values between 0.06 and 0.10 are described as tendencies.

### Results

#### Baseline

Baseline values for body mass,  $VO_{2max}$ ,  $W_{max}$ , gross efficiency, power output at 4 mmol/L, and 40-min all-out trial did not differ between the groups.

#### Mean power output in the interval sessions

During the training period, mean power of work interval sessions had increased by  $9\% \pm 5\%$  in SI group (P < 0.01; Fig. 1), whereas there was no significant change in LI group ( $2\% \pm 5\%$ , P = 0.2). For the second half of the training period, the relative increase in mean power output during work intervals was larger in the SI group than in the LI group (P < 0.05; Fig. 1). There were no difference between the SI group and LI group in RPE after the HIT sessions during training week 1–2 ( $17.4 \pm 1.3$  vs  $17.1 \pm 1.4$ , respectively), training week 3–4 ( $17.6 \pm 0.9$  vs  $17.6 \pm 1.0$ , respectively), training week 5–6 ( $17.9 \pm 0.9$  vs  $17.6 \pm 1.1$ , respectively), training week 7–8 ( $18.2 \pm 0.8$  vs  $17.9 \pm 0.7$ , respectively), and training week 9–10 ( $17.7 \pm 0.9$  vs  $17.8 \pm 0.7$ , respectively).

### Body mass, VO<sub>2max</sub>, and W<sub>max</sub>

Body mass did not change significantly during the intervention in either the SI group  $(76.2 \pm 5.3 \text{ kg vs} 77.1 \pm 5.1)$  or the LI group  $(77.0 \pm 7.2 \text{ vs} 76.9 \pm 7.2)$ . SI training increased VO<sub>2max</sub> by  $8.7\% \pm 5.0\%$  (P < 0.05), whereas there was no significant increase after LI training ( $2.6\% \pm 5.2\%$ , P = 0.28; Fig. 2). W<sub>max</sub> increased by  $8.5\% \pm 5.2\%$  in SI group (P < 0.05) but did not change significantly in the LI group ( $1.6\% \pm 3.6\%$ , P = 0.33; Fig. 3). The percentage increase in VO<sub>2max</sub> and W<sub>max</sub> was larger in the SI group than the LI group ( $P \le 0.05$ ), and the mean ES of the relative improvement in W<sub>max</sub> and VO<sub>2max</sub> revealed a large effect of SI training vs LI training (ES = 1.20 and ES = 1.54, respectively).



*Fig.* 2. Individual data points for (a) maximal oxygen consumption, (b) power output (W) at 4 mmol/L [La<sup>-</sup>], (c) mean power output during the 5-min all-out trial, and (d) mean power output during the 40-min all-out trial before (pre) and after the intervention period (post) for the short-interval group (SI) and the long-interval group (LI). Data points in bold with black squares represent mean values for each data set. \*Larger than at pre (P < 0.05). #The change from pre is larger than in LI (P < 0.05). #Tendency toward larger than pre (P < 0.08).



*Fig. 3.* Power profile before (pre) and after the intervention period (post) in the short-interval training group (SI group; left panel) and the long-interval training group (LI group; right panel). Note that the *x*-axis is not continuous but is composed of tests with different durations. \*Significantly larger than pre (P < 0.05). <sup>£</sup>Tendency toward larger than pre (P = 0.08). <sup>#</sup>The change from pre is larger than in LI (P < 0.10).

### Power output at 4 mmol/L

SI group increased power output at 4 mmol/L [La<sup>-</sup>] by  $12\% \pm 9\%$  (P < 0.01), and there was a tendency toward improvement in LI group  $(5\% \pm 6\%, P = 0.08; \text{Fig. 2})$ . There were no statistical significant differences between groups in changes (P = 0.12), but the ES analysis revealed a moderate practical effect of SI compared with LI training (ES = 0.86). There was no difference between the groups in either gross efficiency or cycling economy, and no change in these measurements was observed in either group during the intervention period. Gross efficiency at a power output of 125, 175, and 225 W was  $16.6\% \pm 1.3\%$ ,  $18.2\% \pm 1.0\%$ , and  $19.0\% \pm 1.0\%$ , respectively, whereas the cycling economy at these power outputs were  $0.232 \pm 0.022$ ,  $0.211 \pm 0.019$ , and  $0.200 \pm 0.019$  mL/ kg/W, respectively, as mean values across groups and time points of intervention.

### Power output in all-out trials

Both the SI and the LI group increased their mean power output during the 40-min all-out trial  $(12\% \pm 10\% \text{ vs})$  $4\% \pm 4\%$ , respectively,  $P \le 0.05$ ; Fig. 2). There was a tendency toward larger relative improvement in mean power output during the 40-min all-out trial in the SI group (P = 0.056), and the ES of the relative improvement revealed a moderate effect of SI compared with LI training (ES = 1.09). [La<sup>-</sup>] values obtained after 40-min all-out tests were not different between the SI and LI groups either at the pretest  $(11.8 \pm 2.4 \text{ and}$  $11.5 \pm 3.4$  mmol/L, respectively) or at the posttest  $(11.5 \pm 2.7 \text{ and } 10.8 \pm 3.2 \text{ mmol/L}, \text{ respectively})$ . Mean [La<sup>-</sup>] from the first 20 min of the 40-min all-out posttest showed a tendency toward higher values in SI group compared with LI group ( $6.2 \pm 1.6$  vs  $4.5 \pm 1.6$  mmol/L, respectively, P = 0.07), whereas there were no differences in mean [La-] values during the last 20 min of the test  $(9.1 \pm 2.1 \text{ vs } 7.9 \pm 3.4 \text{ mmol/L}, \text{ respectively,})$ P = 0.4). Neither at pretests nor at posttests were there any difference between SI and LI groups in [La<sup>-</sup>] values immediately after the 40-min all-out trial (pre:  $11.8 \pm 2.4$ vs  $11.5 \pm 3.4$  mmol/L, respectively; post:  $11.5 \pm 2.7$  and  $10.8 \pm 3.2$  mmol/L, respectively). SI training improved mean power output during the 5-min all-out test by  $8\% \pm 7\%$  (P < 0.01; Fig. 2), whereas there was no significant change after LI training  $(3\% \pm 7\%, P = 0.5;$ Fig. 2). There was no statistically significant difference between groups in relative change but the ES of the relative improvement revealed a moderate effect of SI training vs LI training (ES = 0.71). The  $5\% \pm 3\%$ increase in mean power output during the 30-s Wingate test in the SI group (from  $775 \pm 66$  to  $811 \pm 61$  W, P < 0.01) tended to be larger (P = 0.10) than the nonsignificant change of  $1.4\% \pm 3.7\%$  in the LI group (from  $703 \pm 119$  to  $715 \pm 133$  W, P = 0.3). ES of the relative improvement revealed a moderate effect of SI training vs LI training (ES = 1.03). The average increase in power output from all five tests was 6.9% points higher for the SI group ( $10.0\% \pm 5.8\%$  increase) than the LI group ( $3.1\% \pm 3.2\%$  increase, P < 0.05; Fig. 3). The ES of the mean relative improvement revealed a large effect of SI training vs LI training (ES = 1.47).

### Discussion

The primary finding in the present study was that performing HIT as SIs induced superior training adaptations on several endurance and performance measurements, compared with performing HIT as LIs, despite similar effort and work time during the HIT sessions. SI cyclists had a larger relative increase in VO<sub>2max</sub>, W<sub>max</sub>, mean power output during 30-s Wingate test, and tended to show larger increases in power output at 4 mmol/L [La<sup>-</sup>], and mean power output during 40-min all-out trial compared with LI cyclists. Furthermore, the ES of the relative improvement in all measured parameters revealed a moderate-to-large effect of SI training vs LI training.

The present study used effort matching of the groups instead of matching the groups on total work or energy consumption. It has been suggested that the effortmatched assessment is closer to how athletes typically perform their training (Seiler et al., 2013). The present effort matching was successful as shown by similar RPE scores and [La<sup>-</sup>] in the two groups after the HIT sessions. The observed superior effect after SI training compared with LI training is somewhat contradictory to previous studies that have reported similar improvements between the two training regimens (Stepto et al., 1999; Laursen et al., 2002; Laursen et al., 2005; Helgerud et al., 2007). A potential contributor to these different findings might be that the present study used a longer intervention period, increasing the likelihood of detecting effects of small differences in training stimulus, especially among trained athletes. The present intervention period lasted 10 weeks, whereas the other comparable studies lasted only 3-4 weeks (Stepto et al., 1999; Laursen et al., 2002; Laursen et al., 2005) or 8 weeks (Helgerud et al., 2007). In addition, there are some other differences in the design of the SI protocols that might contribute toward explaining the superiority of SI in the present study, and that might be important to consider when designing interval programs. The 2:1 work : recovery ratio and the rather long duration of each series (9.5 min) enables the cyclists to achieve a relatively large cardiovascular stress.

The SI protocol used in the study by Helgerud et al. (2007) was designed as 15-s work periods alternated by 15-s active recovery periods, and it has been observed that time above 90% of VO<sub>2max</sub> is higher during a SI session when the duration of the work periods are 30 s, as in the present study, than shorter work periods (Rozenek et al., 2007; Wakefield & Glaister, 2009). Furthermore, it has been indicated that a work : recovery ratio of 1:1 induces less time spent above 90% of VO<sub>2max</sub> than the 2:1 ratio used in the present study (Rozenek

et al., 2007). This is probably related to longer time to achieve 90% of VO<sub>2max</sub> because of short work periods in combination with longer recovery periods. Based on these rationales, we suggest that a larger training stimulus (time above 90% of VO<sub>2max</sub>) during the present SI training protocol was the primary cause of the larger VO<sub>2max</sub> adaptations in the SI group compared with the LI group. That being said, the participants in the study of Helgerud et al. (2007) were moderately trained (VO<sub>2max</sub> ~55–60 mL/kg/min) and thus a lower training stimulus might be adequate. The cyclists in the present study appear to have a higher training status (VO<sub>2max</sub> ~66 mL/kg/min) and as fitness level increases, so does the importance of HIT and the quality of training required to improve performance (Midgley et al., 2006).

Some other studies have used similar work intervals as the SI training protocol in the present study (Stepto et al., 1999; Laursen et al., 2002; Laursen et al., 2005). However, the combination of higher work intensity (175% of PVO<sub>2max</sub>) with a longer recovery period (4.5 min) in these studies might have led to insufficient stress on the cardiovascular system for trained cyclists. Accordingly, work periods should reach at least 2–3 min to achieve sufficient training adaptations on cardiac function (Buchheit & Laursen, 2013). If the 30-s work periods had been repeated for a sufficient duration with intermittent and much shorter recovery periods, like the present organization of 30-s work intervals interspersed with 15-s active recovery periods, an even larger stimulus would be placed on the cardiovascular system, potentially leading to superior adaptations. However, reducing the recovery period leads to reduced exercise intensity during the work periods, and the ergogenic potential of the supramaximal efforts have been shown in both untrained and trained persons (Burgomaster et al., 2008; Psilander et al., 2010). This ergogenic effect seems to mainly be due to increased oxygen potential within the exercising muscles. The latter is supported by one of the few studies including muscle tissue data from welltrained cyclists, where it was revealed that upstream genetic markers of mitochondrial biogenesis increase to a similar extent after 7 × 30-s "all-out" work periods (4-min recovery periods in between) as  $3 \times 20$ -min work periods at ~87% of VO<sub>2peak</sub> (Psilander et al., 2010). It might be suggested that lowering the exercise intensity to PVO<sub>2max</sub> and largely reducing the recovery periods from 4.5 min to 15 s enables the cyclists to continuously alternate between work and recovery for a relatively long period. This may induce a much larger stimulus on the cardiovascular system (Rønnestad & Hansen, 2013) and it can be hypothesized that the lower exercise intensity (100% vs 175% of PVO<sub>2max</sub>) might be compensated by the longer exercise duration (i.e., larger volume) and thus induce a superior exercise stimulus on both the cardiovascular system and the local muscular oxygen potential.

The present study did not include muscle tissue analysis and it is thus difficult to comment on the local

adaptations within the exercising muscles. It has been suggested that exercise intensity is the key factor for activation of the master regulator, peroxisome proliferator-activated receptor gamma coactivator 1 alpha (PGC-1 $\alpha$ ), of mitochondrial biogenesis (reviewed in Gibala et al., 2012). Several pathways involved in PGC-1 $\alpha$  activation, like adenosine monophosphateactivated protein kinase and calcium/calmodulindependent protein kinase II, seem to be activated in an exercise intensity-dependent manner (Egan et al., 2010). It has also been indicated that the superior activation of PGC-1 $\alpha$  messenger RNA is largely due to increases in muscle recruitment (Edgett et al., 2013). Although highly speculative, it might therefore be hypothesized that the SI group, who actually exercised at approximately PVO<sub>2max</sub> intensity, achieved a larger stimulus on the mitochondrial biogenesis than the LI group, who had a lower exercise intensity because of the longer continuous work periods.

One of the mechanisms behind the importance of HIT on endurance performance maybe related to increased lactate exposure that is suggested to increase mitochondrial biogenesis and the expression of lactate transporters (Brooks, 2009). Despite similar values of [La<sup>-</sup>] after HIT sessions in the present study, it might be speculated that the session consisting of  $3.0 \times 9.5$  min of SIs and thus a longer continuous duration with high [La<sup>-</sup>] gave a better stimulus than the shorter continuously stimulus (although more frequently) achieved during the  $4 \times 5$ min LI sessions. Weston et al. (1997) observed increased muscle buffer capacity after a HIT interval intervention in well-trained cyclists. Furthermore, they observed a correlation between muscle buffer capacity and 40-km time trial performance. Similarly, Laursen et al. (2005) found that different HIT intervals increased the cyclists' ability to tolerate lactate, as manifested by higher [La<sup>-</sup>] during a 40-km time trial. The latter study did indeed not observe any significant difference between SI and LI. However, the SI protocol was the  $12\% \times 175\%$  of  $W_{max}$ with 4.5-min recovery periods, and therefore it could be that the SI protocol in the present study induced a larger volume of lactate stress. Therefore, it might be speculated that a larger exposure to lactate stress could positively affect muscular adaptations. In fact, during the first half of the present 40-min all-out trial at the posttest, [La<sup>-</sup>] in the SI group tended to be higher than in the LI group. This may be interpreted as a higher lactate tolerance in the SI group and we hypothesize that this may explain some of the performance improvement in this group. Unfortunately, [La<sup>-</sup>] was not regularly measured during the pretest; thus, caution must be used in the interpretation of the comparison of groups at the posttest. However, [La-] at the end of the 40-min all-out trial was similar in the two groups at both pre- and posttests, indicating no difference between groups in maximal production of [La-]. Therefore, it is possible to compare the groups at posttest where the results may give some insight into potential mechanisms behind the

observed adaptations. Improved lactate tolerance could in theory also be related to the favorable improvement in 30-s Wingate power output,  $W_{max}$ , and mean power during 5-min all-out test.

It has been suggested that time spent at high exercise intensity (i.e.,  $PVO_{2max}$ ) might have an additive effect on muscular adaptations (Noakes, 1991; Denadai et al., 2006). Therefore, it might be hypothesized that the present SI protocol, with a higher power output and multiple acceleration phases (the start of every 30-s work interval), facilitates a larger stimulus on the neuromuscular system than the LI protocol. This may be evident by the superior improvement in mean 30-s Wingate power output in SI cyclists. It should be mentioned that the SI protocol, with 30-s work intervals, is more specific to the Wingate test than the LI protocol with 5-min work intervals. On the other hand, the LI protocol is more specific to the 5-min all-out test, and even in this test was the SI training superior to the LI training.

The fact that LI did not improve in all measurements after 10 weeks with two HIT sessions per week might be unexpected. However, it is important to remember that the cyclists in both groups had performed approximately one HIT session per week for at least the last 4 weeks prior to start of intervention. In the majority of studies where trained cyclists have been reported to significantly improve endurance measurements after performing two HIT sessions per week, cyclists have entered the intervention period with no HIT training during the last 4-8 weeks (e.g., Weston et al., 1997; Stepto et al., 1999; Rønnestad et al., 2012). The potential to achieve improvements in endurance performance after an intervention period focusing on HIT is larger when no HIT has been performed during the prior 1-2 months (Seiler et al., 2013). Because the LI group performed their HIT sessions with a lower power output, it was somewhat expected that their improvements occurred in the lower power output region of the power profile (Fig. 3). Interestingly, SI training improved all regions of the power profile (Fig. 3), indicating an effective stimulus for multiple adaptations, such as improved neuromuscular

function, buffering capacity, cardiovascular functions, and muscular oxygen potential.

In conclusion, the present study indicates that performing the present SI protocol during the HIT induces superior training adaptations after 10 weeks compared with performing HIT with a more classic LI protocol constituted by  $4 \times 5$ -min work intervals. This was evident from the ES that showed a moderate-to-large effect of SI training vs LI training on all aspects of the power profile.

### **Perspectives**

The importance of HIT to improve endurance performance in well-trained endurance athletes is established (e.g., Laursen, 2010). Continuous work at such high intensities cannot be sustained for a long time and therefore various interval protocols, from SIs to LIs, have been used to accumulate an adequate training stimulus. It is unclear how to best organize the HIT intervals. After 10 weeks of training that included two weekly sessions of HIT, the present SI protocol was found to be superior to the LI protocol with regard to both the high-power region and lower power region of cyclists' power profile. The present SI protocol consisted of 30-s work periods at approximately PVO<sub>2max</sub> intensity separated by 15-s recovery periods consecutively for 9.5 min followed by 2.5-min recovery period. This 9.5-min period was performed three times in one interval session and can thus be recommended as a good method to organize and optimize a HIT session.

**Key words:** Intense cycling exercise, interval training prescription, endurance training, cycling performance, power profile.

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