

Superior performance improvements in elite cyclists following short-interval vs effort-matched long-interval training

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The purpose of this study was to compare the effects of 3 weeks with three weekly sessions (ie, nine sessions in total) of short intervals (SI; $n = 9$; 3 series with 13×30 -second work intervals interspersed with 15-second recovery and 3-minutes recovery between series) against effort-matched (rate of perceived effort based) long intervals (LI; $n = 9$; 4 series of 5-minute work intervals with 2.5-minutes recovery between series) on performance parameters in elite cyclists ($\dot{V}O_{2\max}$ 73 ± 4 mL min⁻¹ kg⁻¹). There were no differences between groups in total volume and intensity distribution of training during the intervention period. SI achieved a larger ($P < .05$) relative improvement in peak aerobic power output than LI ($3.7 \pm 4.3\%$ vs $-0.3 \pm 2.8\%$, respectively), fractional utilization of $\dot{V}O_{2\max}$ at 4 mmol L⁻¹ [La⁻] (3.0 ± 5.8 percent points vs -3.5 ± 2.7 percent points, respectively), and larger relative increase in power output at 4 mmol L⁻¹ [La⁻] ($2.0 \pm 6.7\%$ vs -2.8 ± 3.4 , respectively), while there was no group difference in change of $\dot{V}O_{2\max}$. Improvements in performance measured as mean power output during 20-minute cycling test were greater ($P < .01$) in SI compared with LI ($4.7 \pm 4.4\%$ vs $-1.4 \pm 2.2\%$, respectively). Mean effect size of the improvement in the above variables revealed a small to large effect of SI training vs LI training. The data thus demonstrate that the present SI protocol induces superior training adaptations compared with the present LI protocol in elite cyclists.

KEYWORDS

cycling performance, endurance training, intense cycling exercise, interval training prescription

1 | INTRODUCTION

The importance of high-intensity aerobic training (HIT) to improve endurance performance in well-trained endurance athletes is established (eg, Laursen¹). We have previously demonstrated that effort- and volume-matched, that is, based on rate of perceived exertion (RPE) score and duration, short intervals improves performance in well-trained cyclists (maximal oxygen uptake ($\dot{V}O_{2\max}$) ~ 65 mL min⁻¹ kg⁻¹) to a greater extent than longer intervals.² However, whether

this is also the case for even better-trained athletes remain unexplored and in general data are scarce on how to optimize HIT training in this population.³ HIT can roughly be divided into longer work intervals of ~ 3 -5 minutes at a high exercise intensity or shorter work intervals ~ 15 -45 seconds at even higher exercise intensities.⁴ Different work:recovery ratios have been used, but 2:1 or 1:1 ratios are frequently used.^{5,6} Both short intervals⁷⁻⁹ and long intervals¹⁰⁻¹² have been demonstrated to improve endurance performance or performance-related parameters in already endurance-trained

participants. The few studies that have compared the training effects of shorter and longer intervals in endurance-trained participants usually report similar performance improvements.¹³⁻¹⁵ However, methodological issues including small sample size, short intervention period, differences in volume of HIT, or matching training regimens on total energy expenditure make it somewhat difficult to interpret the results. It has been suggested that matching on energy consumption artificially constrains the training in a manner not representative of how athletes may perform their trainings in real life.¹⁶

Despite improved endurance performance after HIT interventions in endurance athletes, there is often lack of improvements in some or all of the traditional main determinants of endurance performance such as $\dot{V}O_{2\max}$,¹⁷⁻¹⁹ work economy,¹⁹⁻²¹ and fractional utilization of $\dot{V}O_{2\max}$.^{15,20} Other potential contributors to performance improvements include increased skeletal muscle buffering capacity²² and increased ability to perform with high blood lactate concentration ($[La^-]$), manifested by increased $[La^-]$ during time trials.^{11,14} In this regard, we have previously observed indications that short intervals increase the ability to tolerate high $[La^-]$ during a 40-minute cycling performance to a larger extent than longer intervals in well-trained cyclists.² The underlying mechanisms for performance improvements in elite athletes following a training intervention are thus likely to be complex and integrated. With this in mind and with the aim to test the efficacy of short- vs long-interval training, we included a comprehensive test battery comprising of the assessment of $\dot{V}O_{2\max}$, cycling economy, fractional utilization of $\dot{V}O_{2\max}$ at 4 mmol L⁻¹ $[La^-]$, and power output at 4 mmol L⁻¹ $[La^-]$. Endurance performance was determined as mean power during a 20-minute cycling test. Based on our previous results, we hypothesized that short intervals would result in superior improvements in the performance indicators as well as in the 20-minute cycling performance test.

2 | METHODS

2.1 | Subjects

Eighteen male participants at a national level and a mix of road and cross-country mountain bike cyclists volunteered for the study. Based on the peak aerobic power output (W_{\max}), $\dot{V}O_{2\max}$, and training characteristics, the cyclists were regarded elite.²³ The cyclists were assigned and counterbalanced to create two homogenous groups based on $\dot{V}O_{2\max}$: a short-interval group (SI; $n = 9$, age = 24 ± 6 years, body height = 181 ± 4 cm, and body mass = 75.2 ± 3.6 kg) and a long-interval group (LI; $n = 9$, age = 25 ± 6 years, body height = 183 ± 4 cm, and body mass = 74.9 ± 6.1 kg). During the 3 weeks prior to the intervention period, SI and the LI cyclists focused on high volume of low-intensity training (LIT;

60%-82% of peak heart rate [HR_{peak}]) and weekly training volume during this period was 17.4 ± 5.0 and 15.6 ± 5.0 h/wk of LIT training, respectively. In this period SI and LI also performed 1.1 ± 0.3 and 1.0 ± 0.4 weekly hours of moderate-intensity training (MIT; 83%-87% of HR_{peak}), and 0.1 ± 0.2 and 0.1 ± 0.2 weekly hours of high-intensity interval training (HIT; 88%-100% of HR_{peak}), respectively. 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.

2.2 | Experimental design

All testing was performed on one day and started with a incremental cycle test for determination of cycling economy, power output, and fractional utilization of $\dot{V}O_{2\max}$ at a blood lactate concentration of 4 mmol L⁻¹ ($[La^-]$) followed by a $\dot{V}O_{2\max}$ test and a final 20-minute trial to exhaustion. Participants were tested before and after a 3-week intervention period where they focused on HIT and thus performed 3 weekly HIT sessions. In order to investigate the effect SI vs LI, all cyclists performed the same weekly amount LIT, MIT, and HIT with the only difference being that the HIT sessions in SI were designed as multiple short intervals (30-second work intervals separated by 15-second recovery periods), while the HIT sessions in LI was performed as 4×5 minutes work intervals. The intervention was completed during the cyclists' preparatory period.

2.3 | Training intervention

The intervention started after a period with high volume and according to traditional training periodization, the focus during the intervention period changed to higher training intensity and a lower volume.²⁴ The LI group performed 4×5 minutes work intervals separated by 2.5-minute recovery periods, while the SI group performed 30-second work intervals separated by 15-second recovery periods continuously for 9.5 minutes followed by 3-minute recovery period. This 9.5-minute period was performed three times in one HIT session. Thus, the total time of work intervals in one interval session for LI and SI was 20 and 19.5 minutes, respectively, while the total recovery period was 7.5 and 15 minutes, respectively. 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 by using Borg's 6-20 scale.²⁵ Both groups were instructed to perform intervals with their maximal sustainable work intensity, aiming to perform highest possible average power output during each interval session. Similar effort during both the SI training and

the LI training was evident via similar mean RPE across all work intervals (Table 1). At least two of the three weekly HIT sessions were supervised.

Each interval session started with an individual 15-minute warm-up that was concluded by 2-3 submaximal sprints lasting 20-30 seconds. In order to ensure a rapid increase and decrease in power output during the SI training, these sessions were either performed on own bike equipped with PowerTap SL 2.4 power meter (CycleOps) connected to Computrainer Lab™ electromagnetically braked roller (Racer Mate Inc) or performed on a Lode Excalibur Sport ergometer. The individual SI sessions were programmed in the software to the roller and/or ergometer. The power output during the work intervals was individual adjusted between each interval series to ensure optimal individual power output (ie, highest possible average power output during each session). During the HIT sessions in the intervention period, mean power output in the work intervals was higher in SI than LI ($P < .01$, Table 1). During the intervention period, there were no differences between SI and LI in the average weekly duration of the endurance training and the distribution of this training into LIT (7.4 ± 2.3 vs 7.4 ± 1.0 hours, respectively), MIT (1.3 ± 0.8 vs 1.4 ± 1.3 hours, respectively), and HIT (1.1 ± 0.1 vs 1.1 ± 0.2 , respectively).

2.4 | Testing procedures

The cyclists were instructed to refrain from all types of intense exercise the day preceding each test day. 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 hours preceding the tests. All tests were performed under similar environmental conditions (17-20°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 (± 1 hour) to avoid influence of circadian rhythm. The individual amount of water and sports drink consumed during the entire test session was noted during the pre-test and replicated during the post-test. All testing was performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport), 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 during all tests.

2.5 | Blood lactate profile

The blood lactate profile test has been described elsewhere.²⁶ The test started with 5-minute cycling at 125 W followed 50 W increases every 5 minutes. Blood samples were taken from a fingertip at the end of each 5 minutes bout and were analyzed for whole blood $[La^-]$ using a portable lactate analyzer (Lactate Pro LT-1710; Arcray Inc Kyoto). The test was terminated when a $[La^-]$ of 4 mmol L⁻¹ or higher was measured. $\dot{V}O_2$, respiratory exchange ratio (RER), and HR were measured during the last 3 minutes of each bout. HR was measured using a Polar S610i heart rate monitor (Polar, Kempele, Finland). $\dot{V}O_2$ was measured (30 seconds sampling time) using a computerized metabolic system with mixing chamber (Oxycon Pro; Erich Jaeger). 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). The same metabolic system with identical calibration routines was used on all subsequent tests. From this cycling test, power output and fractional utilization of $\dot{V}O_{2max}$ at 4 mmol L⁻¹ $[La^-]$ were calculated. Cycling economy was calculated as the average $\dot{V}O_2$ between 3 and 5 minutes at the power output of 275 W.

2.6 | $\dot{V}O_{2max}$

After termination of the blood lactate profile test, the cyclists had 10 minutes of recovery cycling before completing another incremental cycling test for determination of $\dot{V}O_{2max}$. This test has been described elsewhere.²⁷ Briefly, the test was initiated with 1 minute of cycling at a power output corresponding to 3 W kg⁻¹ (rounded down to the nearest 50 W). Power output was subsequently increased by 25 W every minute until exhaustion, defined as a cadence below 60 rpm. $\dot{V}O_{2max}$ was calculated as the average of the two highest consecutive 30 seconds $\dot{V}O_2$ measurements. W_{max} was calculated as the mean power output during the last minute of the incremental $\dot{V}O_{2max}$ test.

TABLE 1 Characteristics of the performed high-intensity aerobic training (HIT) sessions in the multiple short-interval group (SI) and long-interval group (LI)

	SI	LI
	Mean \pm SD	Mean \pm SD
Number of HIT sessions	8.8 \pm 0.4	8.9 \pm 0.3
Mean power in HIT work intervals (W)	441 \pm 31*	368 \pm 35
% of W_{max} (%)	94 \pm 3*	79 \pm 7
Mean RPE after HIT series (6-20)	17.8 \pm 0.6	17.6 \pm 0.6

Abbreviations: RPE, rate of perceived exertion; W_{max} , peak aerobic power output.

*Significant difference between groups ($P < .05$).

2.7 | 20-minute cycling test

After the $\dot{V}O_{2\max}$ test, the cyclists had 20 minutes active recovery before they performed a 20-minute cycling test. During the last 5 minutes of the recovery period, the cyclists performed two submaximal sprints lasting 30 seconds with increasing power output and they had complete rest during the last minute before test start. The cyclists were instructed to aim for the highest possible mean power output during the 20-minute test and to remain seated during the entire test. The cadence was freely chosen, and the cyclists were allowed to adjust the power output throughout the trial using an external control unit placed next to the handlebar of the Lode Excalibur Sport cycle ergometer. Performance during the 20-minute test was measured as the average power output. Blood lactate concentration was measured every 4th minute.

2.8 | Statistical analyses

All values presented in the text, figures, and tables are mean \pm SD. To test for differences between groups, an analysis of covariance (ANCOVA) was used, with the percent change from pre to post as dependent variable, and the baseline values as a covariate to adjust for possible between-group differences pre-intervention. Pre- and post-intervention measurements for each group were compared using two-tailed paired Students *t* test. Changes within groups in $[La^-]$ during the 20-minute test was evaluated by separate analysis within each group with a two-way repeated measures analysis of variance (ANOVA) with time of intervention period, (pre and post), time during the 20-minute test, and the interaction between them were used as explanatory variables, with Sidak post-hoc tests. Between-group differences in changes in $[La^-]$ during the

TABLE 2 Data from the performance and physiological tests before (pre) and after the intervention period (post) in the multiple short-interval group (SI) and long-interval group (LI). The magnitude of improvements of SI vs LI is also shown

	SI		LI		Magnitude of improvement SI vs LI (ES)
	Pre	Post	Pre	Post	
Body mass (kg)	75.2 \pm 3.6	75.0 \pm 3.6	74.9 \pm 4.9	74.8 \pm 4.8	
$\dot{V}O_{2\max}$ test					
$\dot{V}O_{2\max}$ (L min ⁻¹)	5.53 \pm 0.32	5.66 \pm 0.26*	5.46 \pm 0.50	5.50 \pm 0.63	0.19
(mL min ⁻¹ kg ⁻¹)	73.3 \pm 3.6	75.5 \pm 2.7*	72.7 \pm 4.9	73.6 \pm 6.2	0.31
RER _{peak}	1.10 \pm 0.04	1.11 \pm 0.05	1.15 \pm 0.04	1.14 \pm 0.03	
HR _{end} (beats min ⁻¹)	190 \pm 5	189 \pm 5	193 \pm 6	193 \pm 5	
$[La^-]_{end}$ (mmol L ⁻¹)	10.6 \pm 2.0	11.4 \pm 2.3	12.1 \pm 2.3	13.0 \pm 2.4	
RPE	18.8 \pm 0.7	19.3 \pm 0.8	19.0 \pm 0.7	19.0 \pm 0.5	
W_{max} (W)	460 \pm 26	476 \pm 14*,a	469 \pm 35	468 \pm 34	0.57
Submaximal test					
Power _{4mmol L⁻¹} (W)	334 \pm 37	339 \pm 23 ^a	329 \pm 41	320 \pm 38	0.37
% $\dot{V}O_{2\max@4mmol L-1$ (%)	82.1 \pm 6.7	85.1 \pm 2.2 ^a	83.5 \pm 3.8	80.6 \pm 3.8	1.18
$\dot{V}O_{2@275 W}$ (L min ⁻¹)	4.09 \pm 0.30	4.13 \pm 0.37	3.89 \pm 0.33	3.90 \pm 0.34	
20-min cycling test					
Power _{20-min} (W)	343 \pm 31	358 \pm 24*,a	348 \pm 28	344 \pm 31	0.67
HR _{mean} (beats min ⁻¹)	177 \pm 7	176 \pm 6	179 \pm 6	177 \pm 5	
HR _{end} (beats min ⁻¹)	188 \pm 5	187 \pm 6	188 \pm 8	187 \pm 8	
$[La^-]_{mean}$ (mmol L ⁻¹)	5.35 \pm 1.51	7.45 \pm 2.12*,a	7.66 \pm 2.25	7.62 \pm 1.64	1.11
$[La^-]_{end}$ (mmol L ⁻¹)	9.35 \pm 2.53	10.68 \pm 3.08	12.38 \pm 2.75	11.45 \pm 1.88	
RPE (6-20)	18.9 \pm 0.6	19.3 \pm 1	19.3 \pm 0.9	19.1 \pm 1.0	

Note: Values are mean \pm SD.

Abbreviations: $[La^-]_{end}$, blood lactate concentration one min after exercise; $[La^-]_{mean}$, mean blood lactate concentration during 20-min cycling test; HR_{end}, heart rate at the end of exercise; Power_{20-min}, mean power output during 20-min cycling test; Power_{4mmol L⁻¹}, power output at a blood lactate concentration of 4 mmol L⁻¹; RER_{peak}, peak respiratory exchange ratio; RPE, rate of perceived exertion; W_{max} , peak aerobic power output; $\dot{V}O_{2\max}$, maximal oxygen consumption; % $\dot{V}O_{2\max@4mmol L⁻¹$, fractional utilization of $\dot{V}O_{2\max}$ at the power output at 4 mmol L⁻¹.

*Different from pre (*P* < .05).

^aThe relative change from pre is larger than in LI (*P* < .05).

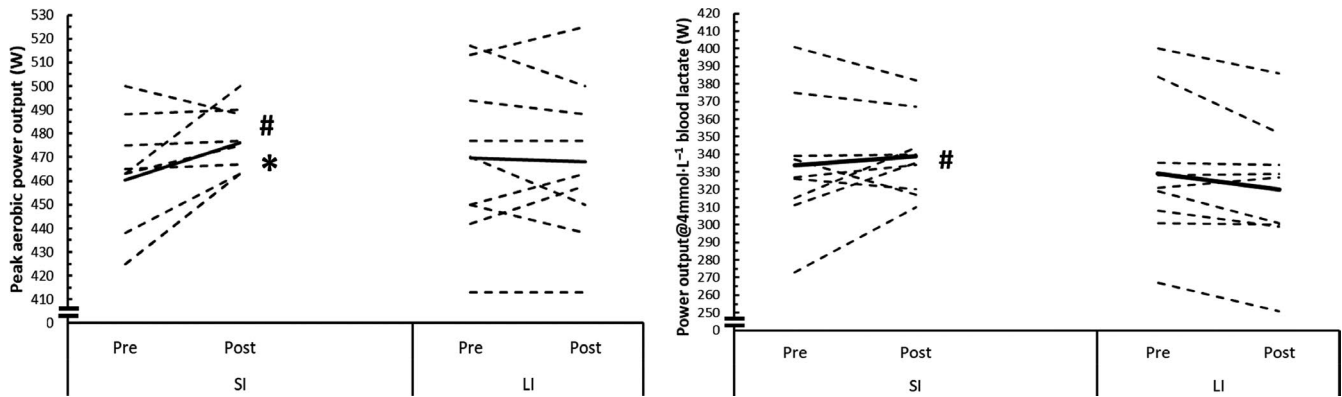


FIGURE 1 Individual data points and mean values (solid line) for peak aerobic power output (left panel) and power output at 4 mmol L⁻¹ blood lactate concentration (right panel) before (pre) and after the intervention period (post) for the short-interval group (SI) and the long-interval group (LI). *Larger than at pre ($P < .05$), #the relative change from pre is larger than in LI ($P < .05$)

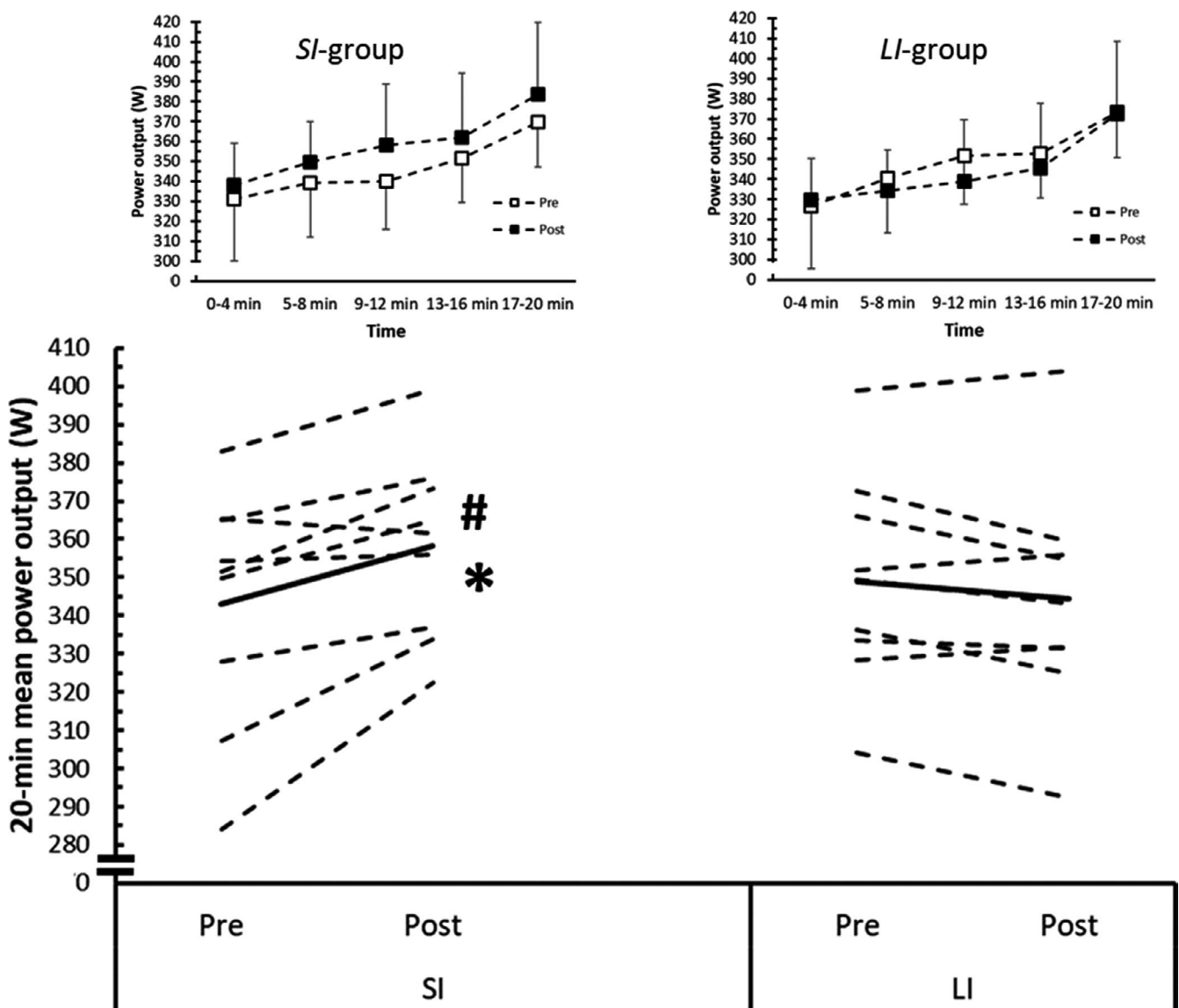


FIGURE 2 Individual data points and mean values (solid line) for mean power output during the 20-min cycling test (lower panel) and development of power output during the 20-min cycling test (upper panels) before (pre) and after the intervention period (post) for the short-interval group (SI) and the long-interval group (LI). *Larger than at pre ($P < .05$), #the relative change from pre is larger than in LI ($P < .05$)

20-minute test were evaluated with the pre-post change as dependent variable and group, time point during tests and the group * time point interaction as explanatory variables, with Sidak post-hoc tests. *t* Tests were performed in Excel 2016 (Microsoft Corporation). ANOVA analyses were performed in GraphPad (GraphPad Software Inc). ANCOVA analysis was performed in IBM SPSS statistics 24. All analyses resulting in $P < .05$ were considered statistically significant, while P -values between .05 and .10 are described as tendencies. Effect size (ES) was calculated as Cohen's *d* by using the mean pre-post change in SI minus the mean pre-post change in LI, divided by the pooled pre-test standard deviation to elucidate on the practical significance of the different HIT protocols.²⁸ The scale proposed by Rhea²⁹ for highly trained subjects was used to interpret the magnitude of the treatment effect; 0.0-0.24 trivial, 0.25-0.49 small, 0.5-1.0 moderate, and >1.0 large.

3 | RESULTS

3.1 | Baseline

There were no differences in any of the physiological or performance measurements between SI and LI before the intervention period (Table 2).

3.2 | Body mass, $\dot{V}O_{2\max}$, and W_{\max}

Body mass did not change during the intervention in any of the two groups (Table 2). There was no difference between the groups in percentage change of $\dot{V}O_{2\max}$, although there was an increase within SI by $2.6 \pm 2.7\%$, ($P < .05$) and no change in LI ($0.9 \pm 3.6\%$, $P = .39$; Table 2). SI had a larger

($F = 5.02$, $P < .05$) percentage increase in W_{\max} than LI. The within-group increase in W_{\max} in SI was $3.7 \pm 4.3\%$ ($P < .05$), while LI did not change ($-0.3 \pm 2.8\%$, $P = .73$; Figure 1).

3.3 | Cycling economy, power output at 4 mmol L^{-1} and 20-minute cycling test

There was no change in cycling economy in any of the groups (Table 2). The fractional utilization of $\dot{V}O_{2\max}$ at the power output at $4 \text{ mmol L}^{-1} [\text{La}^-]$ was more improved ($F = 18.85$, $P < .01$, Figure 1) in SI than LI (Table 2), with no changes within SI (3.0 ± 5.8 percent points, $P = .16$) and a reduction within LI (-3.5 ± 2.7 percent points, $P < .01$). The percent change in power output at $4 \text{ mmol L}^{-1} [\text{La}^-]$ was larger in SI than in LI ($F = 5.56$, $P < .05$, Table 2), but not significantly changed within SI ($2.0 \pm 6.7\%$, $P = .49$) or LI (-2.8 ± 3.4 , $P = .05$). There was a larger ($F = 14.43$, $P < .01$) percentage improvement in mean power output during the 20-minute test in SI than LI (Table 1). Within groups, there was an increase ($P < .01$) by $4.7 \pm 4.4\%$ in SI, with no significant change in LI ($-1.4 \pm 2.2\%$, $P = .11$, Figure 2). Adjustment for pre- to post-changes in RPE or HR during the 20-minute test did not affect the superiority of SI vs LI in power output ($F = 16.97$, $P < .01$ and $F = 11.50$, $P < .01$ for RPE and HR adjusted power output respectively), and there was no significant difference between SI and LI in mean HR or RPE neither at the pre-test nor at the post-test (Table 2). At post-test, SI increased ($P < .01$) $[\text{La}^-]$ from the second time point and throughout the 20-minute trial, while no changes occurred in LI (Figure 3). SI had a larger ($P < .01$) increase in mean $[\text{La}^-]$ during the 20-minute trial from pre- to post-test than LI (Table 2), with a larger ($P < .01$) relative increase at the 8th, 12th, and 16th minute of the test (Figure 3).

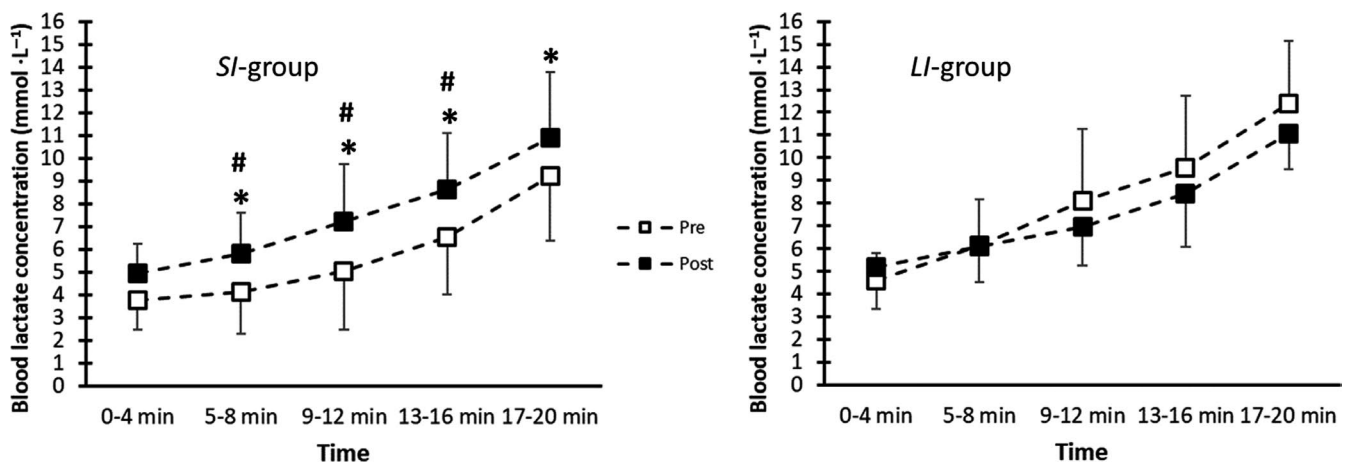


FIGURE 3 Mean blood lactate concentrations during 20-min cycling test before (pre) and after the intervention period (post) for the short-interval group (SI) and the long-interval group (LI). *Larger than at pre ($P < .05$), #the relative change from pre is larger than in LI ($P < .05$)

4 | DISCUSSION

The primary findings in the present study support our stated hypothesis that SI induces superior training adaptations on endurance and performance parameters compared with LI in elite cyclists. Furthermore, the ES of the improvements revealed a small to large effect of SI vs LI. This occurred despite similar effort and work time during the HIT sessions.

A unique feature of the present study is that unlike most previous studies focusing on interval training strategies where the performed work is either matched for total work or energy consumption, the matching in the present study was for perceived effort. While the traditional approach may clearly have its scientific advantages, this approach may also create a training situation not compliant with real world training, and indeed, it has been suggested that perceived effort-matched assessment is closer to how athletes typically perform their HIT training sessions.¹⁶ With this in mind, we decided to apply perceived effort and volume matching of the groups. The approach was successful as demonstrated by similar RPE scores after all work intervals in the two groups.

Regarding $\dot{V}O_{2\max}$, our findings are in agreement with a similar intervention performed with less trained cyclists ($\dot{V}O_{2\max} \sim 65 \text{ mL min}^{-1} \text{ kg}^{-1}$).² However, our findings are also somewhat contradictory to previous studies that have reported similar improvements following SI and LI training in trained to well-trained endurance athletes.^{13-15,17} The discrepancy might be due to differences in the design of the SI protocols. The SI protocol used by Helgerud et al¹⁵ was designed as 15-second work periods alternated by 15-seconds active recovery periods and it has been observed that time above 90% of $\dot{V}O_{2\max}$ is higher during a SI session when the duration of the work periods is 30 seconds, as in the present study.^{6,30} Furthermore, it has been indicated that a work:recovery ratio of 1:1 induces less time spent above 90% of $\dot{V}O_{2\max}$ than the 2:1 ratio applied in the present study.⁶ Based on these rationales, it might be suggested that the training stimulus, defined as time above 90% of $\dot{V}O_{2\max}$, was larger in the present SI protocol and thus larger adaptations might be expected. That being said, the participants in the study of Helgerud et al¹⁵ were moderately trained ($\dot{V}O_{2\max} \sim 55\text{--}60 \text{ mL min}^{-1} \text{ kg}^{-1}$) and a lower training stimulus may have been adequate to induce adaptations. The elite cyclists in the present study had a higher training status ($\dot{V}O_{2\max} \sim 73 \text{ mL min}^{-1} \text{ kg}^{-1}$) with a likely increased demand of stimulus to induce further adaptation, emphasizing the need for high-quality training sessions for this athlete population.⁵ Previous studies with similar short duration interval protocols^{13,14,17} have used a higher work intensity (175% of W_{\max}) and a longer recovery period (4.5 minutes) between intervals and found no difference in adaptations compared with longer intervals. These short-interval sessions might not stress the cardiovascular system of trained cyclists to a sufficient degree. However, reducing the

recovery periods leads to reduced exercise intensity during the work periods, and an ergogenic potential of supramaximal efforts have been demonstrated also in well-trained cyclists.³¹ At the mechanistic level, it would be expected that the improvements in $\dot{V}O_{2\max}$ would mainly be related to concomitantly occurring changes in O_2 transport capacity but since none of the relevant parameters for this were assessed, this remains speculative.

In terms of exercise performance, it has previously been observed that improved 40 km time-trial performance is accompanied by an increase in $[La^-]$ from 5.1 to 7.5 mmol L^{-1} during the trial.¹¹ Furthermore, increased muscle buffer capacity in well-trained cyclists correlates with improved 40 km time-trial performance.²² In a similar manner, Laursen et al¹⁴ found that different HIT intervals increased the cyclists' ability to tolerate lactate, with a correlation between increased $[La^-]$ and improved performance. The latter study did indeed not observe any difference between short and long intervals. However, the short-interval protocol of that study consisted of $12 \times 175\%$ of W_{\max} with 4.5-minute recovery periods, and considering that the present 3×9.5 minutes SI protocol may have induced a larger volume of lactic stress, this may have induced superior skeletal muscle adaptations. In the present study, SI resulted in larger increase in $[La^-]$ during the 20-minute cycling test than LI. This indicates improved ability to perform with high $[La^-]$. It could perhaps be feared that higher $[La^-]$ at post-test may have been caused by less effort at pre-test, but since mean HR, end $[La^-]$, and RPE after the 20-minute cycling test indicates similar effort this seems unlikely. Another potential explanation for the superior improvement in SI could be related to the higher mean power output in the work intervals (94% and 79% of pre- W_{\max} , respectively). In line herewith, it has been reported that volume-matched HIT intervals at 100% of W_{\max} induce superior gene expression of PGC-1 α which could have led to greater mitochondrial biogenesis, compared with HIT intervals at 73% and 130% of W_{\max} in recreational trained participants.³²

The fact that LI did not improve in any measurement after 3 weeks with three HIT sessions per week might be unexpected since previous studies on cyclists with a lower $\dot{V}O_{2\max}$ ($\sim 65 \text{ mL min}^{-1} \text{ kg}^{-1}$) have found that 3-6 weeks with two long-interval sessions per week can improve $\dot{V}O_{2\max}$, W_{\max} , or time-trial performance.^{10,11,13} On the other hand, Nimmerichter et al³³ utilized a long-interval intervention, similar to the one performed by the LI group in the present study, and they also failed to confirm previously reported improvements in $\dot{V}O_{2\max}$, W_{\max} , or power output at ventilatory threshold. It is also important to acknowledge that the high training status of the included cyclists in the present study combined with the short intervention period makes it difficult to achieve significant changes. Indeed, the reduction in weekly training hours, although the training intensity

increased, might also contribute to explain no significant improvement within the LI group. However, the SI group had the same reduction in weekly training hours and experienced performance improvement. As expected, there were no changes in cycling economy in any of the groups during this short 3-week intervention period. Although seasonal changes in gross efficiency are reported,^{34,35} a stable cycling economy is in accordance with previous observations in cyclists, especially for highly trained cyclists and during such a short period of time.^{26,36}

Some limitations of the present study may be related to the experimental design, specifically the small sample size, short intervention period, decrease in weekly training hours during the intervention period, the subjective nature of RPE, and the fact that all the tests were carried out on the same day. However, it could also be argued that finding group differences after only 3 weeks of intervention, with few and highly trained persons in each group, is interesting. Furthermore, some of the measurements are motivation-related variables, which is the case for most performance measurements, and although we cannot rule this out, there could be systematic group differences in motivation from pre to post-test. However, when the main performance measurement, mean power output during 20-minute cycling test, was adjusted for pre to post changes in RPE and HR, that did not change the superiority of SI.

In conclusion, the present study demonstrates that performing the present SI protocol, constituted by three series of 9.5 minutes with continuously 30-second work intervals separated by 15-second active recovery periods, induces superior training adaptations compared to performing HIT with a more classic LI protocol.

5 | PERSPECTIVES

The importance of HIT to improve endurance performance in well-trained endurance athletes is established (eg, Laursen).¹ Continuous work at such high intensities cannot be sustained for a long time, and therefore, various interval protocols ranging from short intervals to long intervals have been applied to accumulate an adequate training stimulus. It is unclear how to best organize the HIT intervals. Furthermore, elite cyclists have a very long race season with a corresponding short preparatory period before entering a new race season. Taking into account that they need some vacation from cycling followed by a larger volume of low-intense endurance training and threshold training, there might often only be a sub-optimal period to prioritize focus on HIT training. The present study demonstrates that subsequent to a training period focusing on high training volume, can a 3-week period with three weekly multiple short intervals induce superior training adaptations compared with longer intervals. The

findings would be strengthened if reproduced after a longer training intervention and preferably with inclusion of muscle biopsies or other methodological approaches to investigate the underlying mechanisms.

ACKNOWLEDGEMENTS

The authors thank Mathilde Victoria Thommessen, Steinar Åstrøm and Hanne Berg Eriksen for their help in data collection. We also thank the dedicated group of test cyclists who made this study possible.

CONFLICT OF INTEREST

There is no conflict of interest.

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How to cite this article: Rønnestad BR, Hansen J, Nygaard H, Lundby C. Superior performance improvements in elite cyclists following short-interval vs effort-matched long-interval training. *Scand J Med Sci Sports*. 2020;30:849–857. <https://doi.org/10.1111/sms.13627>