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REVIEW

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A microcycle of high-intensity short-interval sessions induces improvements in indicators of endurance performance compared to regular training

Guro Strøm Solli[1] | Ingvill Odden[2] | Vetle Sælen[2] | Joar Hansen[2] | Knut Sindre Mølmen[2] | Bent R. Rønnestad[2]

[1]Department of Sport Science and Physical Education, Nord University, Bodø, Norway

[2]Inland Norway University of Applied Sciences, Section for Health and Exercise Physiology Lillehammer, Lillehammer, Norway

Correspondence
Bent R. Rønnestad.
Email: bent.ronnestad@inn.no

Abstract

The purpose of this study was to evaluate the effects of a microcycle of high-intensity interval training (HIT) sessions with multiple short work intervals followed by an active recovery period, compared to a similar duration of regular training, on determinants and indicators of endurance performance in well-trained cyclists. The participants in the BLOCK group performed a 6-day HIT microcycle including five HIT sessions (5 × 8.75-min 30/15 s short intervals) followed by a 6-day active recovery period with reduced training load, while the regular training group (REG) performed 12 days of their regular training, including four HIT sessions. Physiological testing was performed before and after the training periods. From pre- to post- intervention, BLOCK demonstrated significantly larger improvements than REG in mean power output (PO) during the last min of the maximal oxygen uptake (VO_{2max}) test (PO_{VO2max}) (3.7 vs. 0.7%, $p = 0.009$, and effect size (ES) = 1.00) and mean PO during the 10-s sprint (2.8 vs. 1.9%, $p = 0.028$, and ES = 0.63). No significant differences between BLOCK and REG were observed for VO_{2max}, PO at 4 mmol·L^{-1} [blood lactate] (PO_{4mmol}), 15-min maximal mean power output ($PO_{15\text{-}min}$), and gross efficiency ($p = 0.156$–0.919). However, there was a tendency for larger improvements in the performance index (calculated from the main performance indicators PO_{VO2max}, PO_{4mmol}, and $PO_{15\text{-}min}$) in BLOCK compared to REG (2.9% vs. 1.2%, $p = 0.079$, and ES = 0.71). A 6-day high-intensity short-interval microcycle followed by a 6-day active recovery period induces improvements in endurance performance indicators compared to regular training, demonstrating its potential as an efficient strategy for endurance training in well-trained cyclists.

KEYWORDS
cycling, endurance training, high-intensity aerobic training, high-intensity intermittent training, intense exercise

Guro Strøm Solli and Ingvill Odden contributed equally to this work.

Highlights

- This study evaluated the effects of a microcycle of high-intensity interval training (HIT) sessions with multiple short work intervals followed by an active recovery period against regular endurance training in well-trained cyclists.
- A 6-day HIT microcycle followed by a 6-day active recovery period induces improvements in indicators of endurance performance compared to a similar time period of regular training.

1 | INTRODUCTION

The key training variables—frequency, duration, and intensity—must be carefully considered when designing the optimal training program for developing endurance performance. Retrospective training analysis shows that endurance athletes typically perform high amounts of low-intensity training (LIT) interspersed with one to three moderate or HIT (MIT and HIT, respectively) sessions over a week (Solli et al., 2017; Stöggl & Sperlich, 2015; Torvik et al., 2021; Tønnessen et al., 2014). However, to accelerate the development of key performance-related variables, different strategies entailing an increased number of HIT sessions over a relatively short period (5–14 days), referred to as an HIT microcycle, have been investigated in well-trained endurance athletes (Karlsen et al., 2020; Rønnestad et al., 2014a, 2014b, 2016; Solli et al., 2019).

HIT is typically designed to elicit an intensity of ≥90% of maximal oxygen uptake ($\dot{V}O_{2max}$) to induce optimal adaptations of the oxygen delivery and utilization system. Aerobic HIT can be categorized into two main types, including traditional or "long" intervals (e.g., ~2–10 min with 2–3 min of recovery) and intermittent or "short" aerobic intervals (15–60 s work periods with 2:1 or 1:1 active recovery periods) (Stöggl et al., 2024). Both long and short aerobic intervals have been demonstrated to improve endurance performance or performance-related indicators in endurance-trained participants (Iaia et al., 2008; Rønnestad, Ellefsen, et al., 2014; Tabata et al., 1996). The majority of studies investigating the effect of an HIT microcycle have shown improvements in both $\dot{V}O_{2max}$ and performance-related variables compared with the traditional approach with an even distribution of HIT sessions (Breil et al., 2010; Rønnestad, Hansen, & Ellefsen, 2014; Rønnestad & Vikmoen, 2019), while some studies report improvements only in performance measures (Clark et al., 2014; Rønnestad et al., 2016, 2022; Wahl et al., 2013). Rønnestad et al. (2021) reported superior improvements in indicators of endurance performance through using multiple short intervals (five series of 12 30-s work intervals interspersed with 15 s of active recovery) compared with longer intervals (six 5-min work intervals) in well-trained cyclists. This indicates that the inclusion of HIT sessions with multiple short work intervals into a microcycle could be particularly beneficial for this population.

To effectively incorporate a microcycle consisting of HIT sessions with multiple short work intervals followed by an active recovery period with reduced training load into long-term training programs, it is essential to understand its efficiency compared to the traditional approach of an even distribution of one to three intensive sessions per week combined with LIT. However, no previous study has investigated this in cyclists. Therefore, the purpose of the present study was to compare the effects of a high-intensity short-interval microcycle followed by an active recovery period with regular training of similar duration on endurance performance indicators and determinants in well-trained cyclists. Based on prior findings, we hypothesized that the high-intensity short-interval microcycle and active recovery period would lead to greater improvements in endurance performance indicators and determinants compared to regular training.

2 | METHODS

2.1 | Participants

Thirty-eight cyclists (34 male and 4 female) initially volunteered to participate in the study, which was performed during the cyclists' preparatory period (in January and February, that is, ~1–2 months before the start of the competition season). The study was performed according to the ethical standards established by the Declaration of Helsinki and was approved by the local Ethics Committee. All participants provided informed consent. Five cyclists withdrew from the study after the pre-intervention test because they thought the test protocol was too hard and/or did not complete the test protocol. Consequently, these participants were excluded from the statistical analyses. In total, 22 cyclists (21 male and 1 female) completed the HIT microcycle and the active recovery period (BLOCK group) [mean (standard deviation (SD)): age: 20.1 (3.6) years, body mass: 71.2 (8.4) kg, body height: 181 (7) cm, and $\dot{V}O_{2max}$: 71.1 (6.5) ml·min^{-1}·kg^{-1}] and 11 cyclists (9 male and 2 female) completed the regular training period (REG group) [age: 23.2 (4.9) years, body mass: 72.5 (7.4) kg, body height: 180 (7) cm, and $\dot{V}O_{2max}$: 71.1 (8.3) ml·min^{-1} kg^{-1}]. The participants had a history of 4.3 (3.0) years of competitive cycling and based on their initial $\dot{V}O_{2max}$, categorized as cyclists at performance level 3 (*n* = 4), 4 (*n* = 6), and 5 (*n* = 23) (De Pauw et al., 2013; Decroix et al., 2016).

2.2 | Experimental design

The present study presents data from a training study investigating the effects of block periodization of endurance exercise training in well-trained cyclists (preregistration DOI: https://doi.org/10.17605/OSF.IO/9AFVD). The main objective of the present study was to compare the effects of an HIT microcycle followed by an active

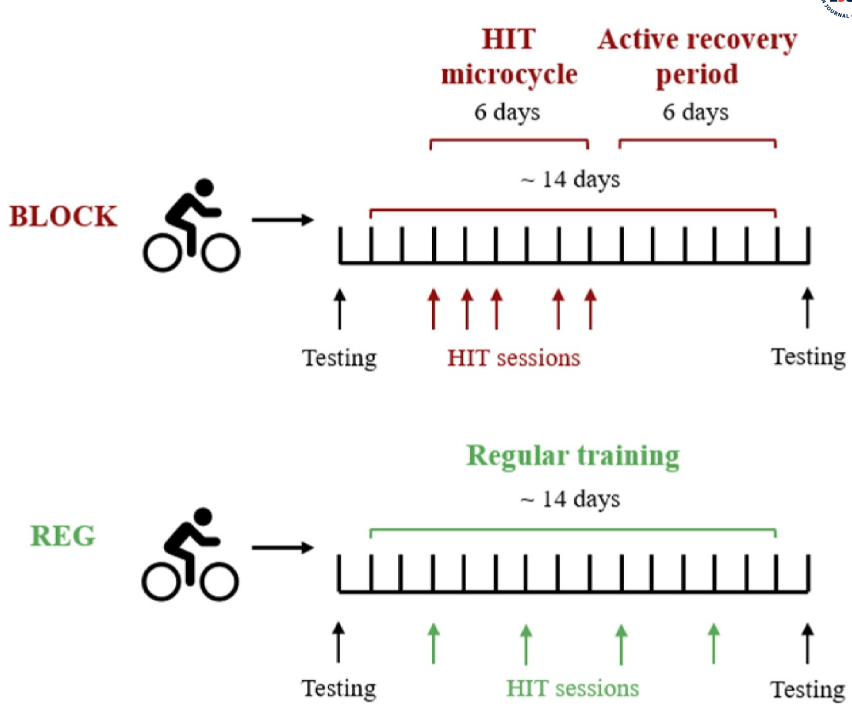

FIGURE 1 Outline of the study design. The BLOCK group performed a 6-day high-intensity interval training (HIT) microcycle followed by a 6-day active recovery period with reduced training load. The regular training group (REG) group continued to perform their regular training for the similar time period, including two HIT sessions per week. Physiological testing was performed before and after the training periods.

recovery period with reduced training load on indicators and determinants of endurance performance with a similar time period of regular training in well-trained cyclists (Figure 1). For both the BLOCK and REG groups, physiological tests were performed before and after the training intervention. Two days of standardized training were performed before each day of testing, consisting of complete rest on the first day and a session including LIT, MIT, and HIT on the second day. After pretesting, participants underwent complete rest on the first day and a 1–2 h LIT session on the second day. The participants in the BLOCK group performed a 6-day HIT microcycle including five HIT sessions consisting of series with multiple short work intervals followed by a 6-day active recovery period with reduced training load. The participants in REG were asked to continue with their regular training program, which included LIT and four HIT sessions evenly distributed over the 12-day period (two HIT sessions per week).

2.3 | Exercise testing procedures

The participants' nutritional intake was similar before each test. Each participant was asked to log their final three meals, fluid, and caffeine intake prior to the first test and to replicate this before the post-intervention test. The nutritional energy intake during pretesting was noted and subsequently repeated at the following test. Each participant had the same test leader during all tests, and verbal encouragement was given to ensure maximal effort in each test. To avoid any influence of the circadian rhythm, the respective tests were performed at the same time of the day (±2 h) for each participant.

2.4 | Maximal isokinetic and isometric unilateral knee-extension torque

The day of exercise testing was initiated with a 7-min standardized cycling warm-up (2 min at an intensity corresponding to a rate of perceived exertion (RPE) of 11 on the 6–20 Borg scale (Borg, 1970), 2 min at an RPE of 13, 1 min with progressively increasing intensity up to an RPE of 15, and 2 min at an RPE of 12). Maximal isokinetic unilateral knee-extension torque was measured at two angular speeds (60°·s^{-1} and 240°·s^{-1}) for a randomized leg using a dynamometer (Humac Norm; CSMi, Stoughton, MA, USA). After performing three repetitions for familiarization, participants were given four and five attempts in immediate succession at the two angular speeds, respectively, with 1.5 min of rest between sets. The highest value obtained at each angular speed was used in further analyses (modified version of the protocol described in detail by Mølmen et al. (2021)).

2.5 | Prolonged cycling test

Five minutes after the knee-extension torque tests, a prolonged cycling test was initiated on an electromagnetically braked cycle

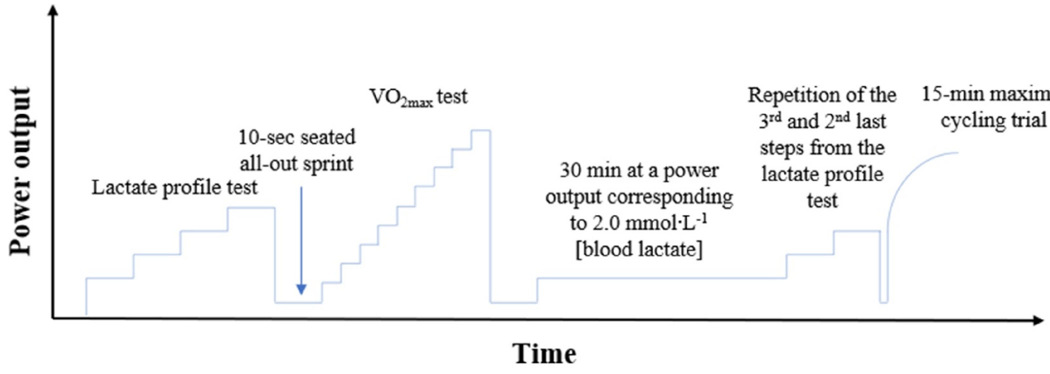

FIGURE 2 An overview of the prolonged cycling test, consisting of (1) a lactate profile test, (2) 5 min of active recovery, (3) a 10-s seated all-out sprint, (4) 5 min of active recovery, (5) a $\dot{V}O_{2max}$ test, (6) 5 min of active recovery, (7) 30 min at a power output corresponding to 2.0 mmol·L^{-1} [blood lactate], with repetition of the third- and second-last 5-min step from the lactate profile test, (8) 1 min of rest, and (9) a 15-min maximal cycling trial.

ergometer (Lode Excalibur Sport, Groningen, The Netherlands) adjusted according to each participant's preferences (Figure 2; test protocol described in detail by Rønnestad et al. (2022)).

Briefly, the participants first performed an incremental blood lactate profile test consisting of 5.5-min work bouts for each workload until the whole blood lactate concentration ([La$^-$]; Biosen C-line Lactate Analyzer, EKF Diagnostic GmbH, Barleben, Germany) measured from the fingertip exceeded 4 mmol·L^{-1}. $\dot{V}O_2$ and the respiratory exchange ratio (RER) were measured (30-s sampling time) from 2.5 to 5 min in each bout (Vyntus Jaeger CPX, Vyaire Medical GmbH, Hoechberg, Germany). From the blood lactate profile test, the power output (PO) corresponding to 4 mmol·L^{-1} [La$^-$] (PO_{4mmol}) and fractional utilization of $\dot{V}O_{2max}$ at 4 mmol·L^{-1} [La$^-$] (% of $\dot{V}O_{2max}$ at PO_{4mmol}) were calculated by plotting La$^-$ as a function of PO and % of $\dot{V}O_{2max}$ at each 5.5-min bout. Following 5 min of active recovery, a 10-s all-out seated sprint was performed with the torque factor set to 0.70 and 0.85 for females and males, respectively. After 5 min of active recovery, an incremental $\dot{V}O_{2max}$ test was initiated with 25 W increases every min until exhaustion, defined as the cadence dropping <60 revolutions per min. $\dot{V}O_{2max}$ was defined as the mean of the 12 highest consecutive 5-s measurements, and maximal 1-min incremental PO ($PO_{\dot{V}O2max}$) was defined as the mean PO during the final min of the test, while the maximal heart rate (HR_{max}) was defined as the highest achieved value during the test. One min after the test was terminated, La$^-$ was measured.

After 5 min of active recovery, the participants exercised for 30 min at the PO corresponding to 2 mmol·L^{-1} [La$^-$] calculated from the blood lactate profile test. Thereafter, the third- and second-last 5.5-min step from the lactate profile test were repeated, during which HR, $\dot{V}O_2$, and RER were measured (30-s sampling time) from 2.5 to 5 min of each bout. Steady-state $\dot{V}O_2$ and RER were used to calculate exercise efficiency, measured as gross efficiency (GE) at the third- and second-last step from the blood lactate profile test in both fresh and semi-fatigued state. GE was defined as the ratio between mechanical PO and metabolic power input (PI; GE = PI·PO^{-1}·100). PI was calculated by using the $\dot{V}O_2$ and the RER measured at the given PO, and the energetic equivalent of O_2 (Péronnet & Massicotte, 1991) according to the equation of Noordhof et al. (2013) (PI = $\dot{V}O_2$ L·s^{-1}·(4840 J·L^{-1}·RER + 16,890 J·L^{-1}). Following one min recovery after completing the two repeated bouts from the blood lactate profile test, the participants performed a 15-min maximal cycling trial. The participants were instructed to aim for the highest possible mean PO and adjusted the PO themselves using an external control unit placed next to the handlebar of the ergometer setup. HR and $\dot{V}O_2$ were measured continuously during the test, and performance was quantified as the mean PO during the trial. The aim of the applied test battery was to assess both standard physiological parameters typically measured in conventional laboratory tests and exercise performance in a more realistic manner. The multiple steps before the final 15-min maximal cycling trial were designed to induce fatigue, simulating the physiological state commonly experienced toward the end of a cycling race. All cycling tests were performed under similar environmental conditions (18.0 (1.1) °C), with an airflow of 2–3 m·s^{-1} toward the participant's frontal surface.

2.6 | Training

The HIT microcycle consisted of five HIT sessions distributed over 6 days. In consecutive days, except for a rest day on the fourth day, they performed an HIT session with five series of 8.75-min multiple short intervals (30-s at □118% of 40-min maximal sustainable PO interspersed with 15-s at □60% of 40-min maximal sustainable PO). The PO during the HIT sessions was individually adjusted based on the RPE score after each work series, which should fall within the range of 16–18. The interval series were separated by 3 min of recovery, of which the first min was passive, and the remaining were active. The total work series duration was 3 h 42 min. All HIT sessions were initiated by a standardized 15-min progressive warm-up protocol and 5 min of rest before starting the first interval series and ended with 5 min of active recovery.

All interval sessions for the BLOCK group were supervised by a test leader, who assessed the participants' perceived readiness (PR) for the upcoming work interval (Edwards et al., 2011) 45 s prior to each interval series, as well as their RPE immediately after each interval series. The participants in the REG group were instructed to perform their regular training, including two HIT sessions per week, as they usually perform their HIT sessions and during which they reported their PR and RPE themselves. All interval sessions were performed on the participants' own bikes connected to a stationary trainer device. PO and HR were measured continuously during all interval series, using participants' own power meters (Tacx Neo 2/ Wahoo Kickr) and HR monitors. Data from the HIT sessions are presented in Table 1. No differences were observed for the mean duration or the % of $PO_{\dot{V}O2max}$ of the HIT sessions in the BLOCK and REG groups, but higher mean values were observed for both HR and RPE, as well as lower PR values, in the BLOCK compared with the REG group.

In the BLOCK group, the first day in the six-day active recovery period comprised complete rest and the second day consisted of complete rest or 20–40 min of LIT. On the third day, the participants performed 30–90 min of LIT, and, on the fourth day, they performed a session consisting of 20 min of LIT, two 5-min MIT intervals, a 1-min HIT interval with progressively increasing intensity, and 10 min of LIT. The fifth day comprised complete rest, and the sixth day consisted of a session which included 20 min of LIT, two 5-min MIT intervals, three 1-min HIT intervals with progressively increasing intensity, and 10 min of LIT.

The participants recorded their daily physical training in a training diary during the 2-week period before and during the intervention. Endurance training was reported according to a five-zone intensity scale based on the percentage of mean HR during a 40-min cycling trial (Hunter et al., 2019). A training impulse (TRIMP) score was calculated by multiplying the accumulated duration of the intensity by a multiplier for the particular intensity zone (e.g., 1 min at LIT [zones 1 and 2], MIT [zones 3 and 4], and HIT [zone 5] were given a TRIMP score of 1, 2, and 3, respectively). The total TRIMP score was then obtained by summing the results (Lucia et al., 2003).

No difference in the training characteristics were observed between the BLOCK and REG groups during the 2-week period before the training intervention. During the intervention, all participants completed their prescribed HIT sessions, and the training volume in zone 2, TRIMP 1 score, heavy resistance training, and total training volume were higher in the REG group compared with the BLOCK group. There was a tendency for higher volume in zone 5 and TRIMP 3 in the BLOCK group compared with the REG group, whereas there was a tendency for higher total TRIMP in the REG group compared with the BLOCK group. Training characteristics during the 2-week period before and during the intervention for the BLOCK and REG groups are presented in Table 2.

2.7 | Statistical analyses

Data are presented as mean with SD unless otherwise stated. Results were considered statistically significant if $p \leq 0.05$ and described as tendencies if $p < 0.10$ and $p > 0.05$. All data analyses were performed in R (R Core Team, 2018). Potential differences in training load between groups were investigated using linear mixed models fitted with

TABLE 1 Data from the five high-intensity interval training (HIT) sessions in the HIT microcycle performed by the BLOCK group and two of the HIT sessions in the regular training period performed by the REG group, respectively.

	BLOCK						**REG**			
	HIT microcycle						**Regular training period**			
	1	**2**	**3**	**4**	**5**	**Average**	**1**	**2**	**Average**	**Group (*p*)**
PO (W·kg^{-1})	4.15 (0.59)	4.22 (0.53)	4.30 (0.47)	4.29 (0.50)	4.27 (0.56)	**4.25 (0.52)**	4.15 (0.87)	4.57 (0.82)	**4.34 (0.85)**	0.539
% of $PO_{\dot{V}O2max}$ (%)	70.0 (7.1)	71.3 (5.5)	72.7 (4.2)	72.5 (4.8)	72.2 (6.3)	**71.7 (5.7)**	68.9 (10.8)	74.7 (9.8)	**71.5 (10.5)**	0.875
HR (bpm)	176 (8)	174 (10)	174 (7)	173 (9)	173 (8)	**174 (8)**	166 (15)	165 (6)	**166 (11)**	<0.001
% of HR_{max}	91.0 (2.9)	89.8 (4.5)	89.6 (1.8)	89.4 (3.3)	89.4 (2.8)	**89.8 (3.2)**	86.6 (5.9)	87.1 (2.9)	**86.8 (4.6)**	<0.001
[La^-] (mmol·L^{-1})		7.2 (1.7)			7.5 (1.7)	**7.4 (1.7)**				
PR (1–7)	3.0 (0.6)	2.9 (0.8)	3.1 (0.6)	3.0 (0.6)	3.0 (0.6)	**3.0 (0.6)**	3.3 (0.9)	3.6 (1.0)	**3.4 (0.9)**	0.011
RPE (6–20)	17.1 (0.3)	17.0 (0.5)	17.1 (0.6)	17.2 (0.3)	17.1 (0.5)	**17.1 (0.5)**	16.1 (1.5)	16.5 (0.8)	**16.3 (1.3)**	<0.001
sRPE (0–10)	7.0 (1.1)	6.8 (0.9)	7.0 (1.0)	7.1 (1.1)	7.3 (0.8)	**7.0 (1.0)**	7.4 (0.9)	7.5 (1.2)	**7.5 (1.0)**	0.102

Note: PO, average power output during the interval series; % of $PO_{\dot{V}O2max}$, average fraction of the maximal 1-min incremental PO during the maximal oxygen consumption test during the interval series; HR, the average heart rate during the interval series; % of HR_{max}, average fraction of maximal HR during the interval series; [La^-], average blood lactate concentration measured 1-min after each interval series at the second and fifth HIT sessions in the HIT microcycle; RPE, average rating of perceived exertion reported after each interval series; PR, average rating of perceived readiness for the upcoming interval series; sRPE, the session rate of perceived exertion reported 10 min after each interval session. $p \leq 0.05$ indicates significant difference in average values between the HIT microcycle and the regular training period. Bold values indicate the average values across the HIT sessions performed by the BLOCK group and the REG group, respectively.

Abbreviations: HR, heart rate; REG, regular training group; RPE, rate of perceived exertion.

TABLE 2 Training characteristics during the two-week period before and during the ~15-day intervention period for the BLOCK and REG groups, respectively.

	BLOCK		REG	
	Two weeks before the intervention	HIT microcycle and active recovery period	Two weeks before the intervention	Regular training
Zone 1 (<55% of $HR_{40\text{-min}}$; h:m)	07:16 (06:26)	04:04 (02:59)[a]	04:21 (05:17)	05:11 (05:18)
Zone 2 (56%–75% of $HR_{40\text{-min}}$; h:m)	09:27 (06:06)	04:43 (02:27)[a]	09:23 (06:40)	12:50 (07:57)[b]
Zone 3 (76–90 of $HR_{40\text{-min}}$; h:m)	04:41 (03:00)	02:22 (00:51)[a]	04:20 (03:33)	04:06 (02:49)
Zone 4 (91%–105% of $HR_{40\text{-min}}$; h:m)	02:25 (01:17)	03:31 (00:49)[a]	02:17 (01:17)	02:57 (01:51)
Zone 5 (>106% of $HR_{40\text{-min}}$; h:m)	00:30 (00:19)	01:12 (01:08)[a]	00:34 (00:24)	00:32 (00:33)[c]
TRIMP 1	1003 (488)	528 (210)[a]	823 (418)	1081 (449)[b]
TRIMP 2	852 (458)	706 (170)	795 (541)	847 (539)
TRIMP 3	89 (58)	216 (205)[a]	101 (72)	94 (98)[c]
TRIMP total	1944 (753)	1450 (264)[a]	1719 (797)	2022 (723[c]
Heavy resistance training (h:m)	00:54 (01:23)	00:05 (00:16)[a]	00:45 (01:12)	01:40 (01:43)[d, b]
Core training (h:m)	00:11 (00:23)	00:12 (00:27)	00:26 (00:55)	00:16 (00:38)
Total training (h:m)	24:54 (10:10)	16:09 (03:54)[a]	22:05 (10:19)	27:32 (09:38)[b]
Feeling legs (1–9)	4.5 (0.9)	4.4 (0.7)	5.1 (0.8)	5.0 (0.7)

Note: $HR_{40\text{-min}}$, the mean heart rate during a 40-min maximal cycling trial; TRIMP, training impulse; heavy resistance training, resistance training with heavy external load (for instance squats or dead lifts using a barbell with weight plates); core training, resistance training without external load (for instance sit-ups); feeling legs, perceived well-being in the legs where 1 is very very good and 9 is very very bad.

Abbreviations: HR, heart rate; REG, regular training group.

[a]Significantly different from the 2-week period before the HIT microcycle and active recovery period ($p \leq 0.05$).

[b]Significantly different from the HIT microcycle and active recovery period ($p \leq 0.05$).

[c]Tendency to being different from the HIT microcycle and the active recovery period ($p < 0.1$ and >0.05).

[d]Tendency to being different from the 2-week period before the regular training period ($p \leq 0.05$).

training variables as the dependent variable, training period as the independent variable, and the subject indicator as a random effect (lme4 package written for R). Potential differences between HIT sessions in the BLOCK and REG group were investigated using linear models fitted with training variables as the dependent variable and group as the independent variable. Potential differences in training responses between groups were investigated using linear models fitted with post-intervention values as dependent variables, group as the independent variable, and the corresponding pre-intervention value as a covariate (stats package written for R). To increase the statistical power for performance-related measures, a performance index based on the main performance indicators ($PO_{\dot{V}O2max}$, PO_{4mmol}, and $PO_{15\text{-min}}$) was calculated as the mean of the given indicators after normalization ($x_i \cdot max[x]^{-1}$ where x_i is a single observation for one performance indicator and $max(x)^{-1}$ is the maximum value observed across all participants for the given indicator). Cohen's *d* effect size (ES) was calculated to interpret the practical significance of the differences in the percentage change in test variables (%-point change for GE_{175W} and $\%\dot{V}O_{2max}$ at PO_{4mmol}) between groups (using the effsize package written for R). The scale proposed by Rhea (2004) 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 | Physiological responses

Training effects in the BLOCK group and the REG group are presented in Table 3, with group changes and individual responses illustrated in Figure 3. The BLOCK group had significantly greater improvement than the REG group for $PO_{\dot{V}O2max}$ ($W \cdot kg^{-1}$; 3.7% vs. 0.7%, $p = 0.009$, and ES = 1.00) and mean PO during the 10-s sprint (1.5% vs. −0.6%, $p = 0.028$, and ES = 0.63). There was also a tendency for larger improvements in the performance index in the BLOCK group compared to the REG group (2.9% vs. 1.2%, $p = 0.079$, ES = 0.71), and a tendency for reduced % of $\dot{V}O_{2max}$ at PO_{4mmol} in the BLOCK group compared to the REG group (−0.9% vs. 0.7%, $p = 0.085$, ES = −0.70).

However, no significant difference between BLOCK and REG was observed for changes in $\dot{V}O_{2max}$ (2.4% vs. 0.6%, $p = 0.156$, and

TABLE 3 Physiological variables in BLOCK and REG before (pre-) and after (post) the training intervention.

	BLOCK		REG			
	Pre	Post	Pre	Post	Group x time	ES
Body mass (kg)	71.2 (8.4)	71.4 (8.2)	72.5 (7.4)	72.7 (7.3)	0.981	0.04
$PO_{\dot{V}O2max}$ ($W \cdot kg^{-1}$)	5.93 (0.66)	6.15 (0.66)	6.01 (0.71)	6.05 (0.72)	0.009	1.00
PO_{4mmol} ($W \cdot kg^{-1}$)	4.07 (0.50)	4.15 (0.50)	4.14 (0.82)	4.20 (0.83)	0.440	0.33
$PO_{15\text{-}min}$ ($W \cdot kg^{-1}$)	4.30 (0.57)	4.42 (0.61)	4.40 (0.68)	4.48 (0.71)	0.689	0.19
Performance index (arbitrary value, 0–1)	0.771 (0.092)	0.793 (0.094)	0.785 (0.123)	0.795 (0.126)	0.079	0.71
$PO_{10\text{-}sec}$ ($W \cdot kg^{-1}$)	13.64 (1.36)	13.82 (1.24)	12.69 (1.36)	12.61 (1.36)	0.028	0.63
$\dot{V}O_{2max}$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	71.1 (6.5)	72.9 (7.3)	71.1 (8.3)	71.4 (8.0)	0.156	0.53
% of $\dot{V}O_{2max}$ at PO_{4mmol} (%)	79.6 (3.3)	78.8 (3.2)	78.6 (6.6)	79.4 (7.1)	0.085	−0.70
% of $\dot{V}O_{2max}$ at PO_{15min} (%)	85.0 (4.2)	83.4 (3.8)	85.1 (3.0)	84.9 (2.6)	0.225	−0.39
GE 3. last $workload_{fresh}$ (%)	19.6 (1.4)	19.8 (1.5)	20.1 (1.7)	20.1 (1.8)	0.414	0.31
GE 3. last $workload_{tired}$ (%)	19.0 (1.3)	19.3 (1.4)	19.3 (1.8)	19.6 (1.8)	0.919	−0.05
GE 2. last $workload_{fresh}$ (%)	19.9 (1.3)	20.0 (1.2)	20.4 (1.5)	20.3 (1.5)	0.213	0.54
GE 2. last $workload_{tired}$ (%)	19.3 (1.1)	19.5 (1.2)	19.8 (1.5)	19.9 (1.4)	0.476	0.33
Peak isokinetic knee-extension torque ($Nm \cdot kg^{-1}$)						
$60° \cdot sec^{-1}$	2.54 (0.29)	2.52 (0.34)	2.72 (0.32)	2.58 (0.40)	0.016	0.78
$240° \cdot sec^{-1}$	1.63 (0.25)	1.62 (0.24)	1.54 (0.18)	1.50 (0.17)	0.149	0.47

Note: $PO_{\dot{V}O2max}$; maximal 1-min incremental power output during the maximal oxygen consumption ($\dot{V}O_{2max}$) test; PO_{4mmol}, power output at 4 $mmol \cdot L^{-1}$ blood lactate concentration ([La^-]); $PO_{15\text{-}min}$, maximal average power output during the 15-min cycling trial; % of $\dot{V}O_{2max}$ at PO_{4mmol}, fraction of $\dot{V}O_{2max}$ at 4 $mmol \cdot L^{-1}$ [La^-]; % of $\dot{V}O_{2max}$ at $PO_{15\text{-}min}$, fraction of $\dot{V}O_{2max}$ during the 15-min cycling trial; GE 3. last $workload_{fresh}$, gross efficiency measured at the third last workload of the blood lactate profile in the fresh state, GE 3. last $workload_{tired}$, gross efficiency measured at the repeated third last workload of the blood lactate profile in the tired state, GE 2. last $workload_{fresh}$, gross efficiency measured at the second last workload of the blood lactate profile in the fresh state, GE 2. last $workload_{tired}$, gross efficiency measured at the repeated second last workload of the blood lactate profile in the tired state. Values are mean (SD). $p \leq 0.05$ indicates significant difference in absolute change from pre to post between BLOCK and REG. $p < 0.1$ and >0.05 indicates a tendency to difference in absolute change from pre- to post between BLOCK and REG.

Abbreviation: REG, regular training group.

ES = 0.53), PO_{4mmol} (2.1% vs. 1.3%, $p = 0.440$, and ES = 0.33), and $PO_{15\text{-}min}$ (2.8% vs. 1.9%, $p = 0.689$, ES = 0.19). Peak isokinetic knee-extension torque at $60° \cdot s^{-1}$ was reduced in the REG group compared to the BLOCK group (−5.4% vs. −1.2%, $p = 0.016$, and ES = 0.78), whereas there were no group differences at the velocity of $240° \cdot s^{-1}$.

4 | DISCUSSION

The primary findings in the present study support our stated hypothesis that an HIT microcycle followed by an active recovery period produces improvements in indicators of endurance performance compared with regular training. Specifically, BLOCK demonstrated a greater improvement in $PO_{\dot{V}O2max}$ and in mean PO during the 10-s sprint compared with REG. There was also a tendency for greater improvements in the performance index (based on the three main performance indicators). These findings suggest that a high-intensity short-interval microcycle followed by an active recovery period could serve as an efficient training strategy for well-trained cyclists.

The improvements in $PO_{\dot{V}O2max}$ and the tendency for greater improvements in the performance index for the BLOCK compared to the REG group are in line with previous studies showing greater improvements in performance-related variables after block periodization of HIT compared with the traditional approach (even distribution of one to three intensive training sessions per week) (Breil et al., 2010; Rønnestad et al., 2014b, 2022; Rønnestad & Vikmoen, 2019). Noteworthy, the variables included in the performance index have been reported to be valid predictors of endurance performance (Lucía et al., 1998; Noakes et al., 1990). In fact, it has been reported that $PO_{\dot{V}O2max}$ differentiates endurance performance in well-trained cyclists (Lucía et al., 1998). The reason for this is probably that $PO_{\dot{V}O2max}$ incorporates anaerobic capacity and neuromuscular characteristics (Jones & Carter, 2000) in addition to $\dot{V}O_{2max}$ and GE. This is supported by our findings of a greater improvement in mean PO during the 10-s sprint in the BLOCK group compared with the REG group, as well as a reduction in peak isokinetic knee-extension torque at $60° \cdot s^{-1}$ in the REG group compared with the BLOCK group. However, no significant change between training groups was observed for $PO_{15\text{-}min}$, suggesting that block

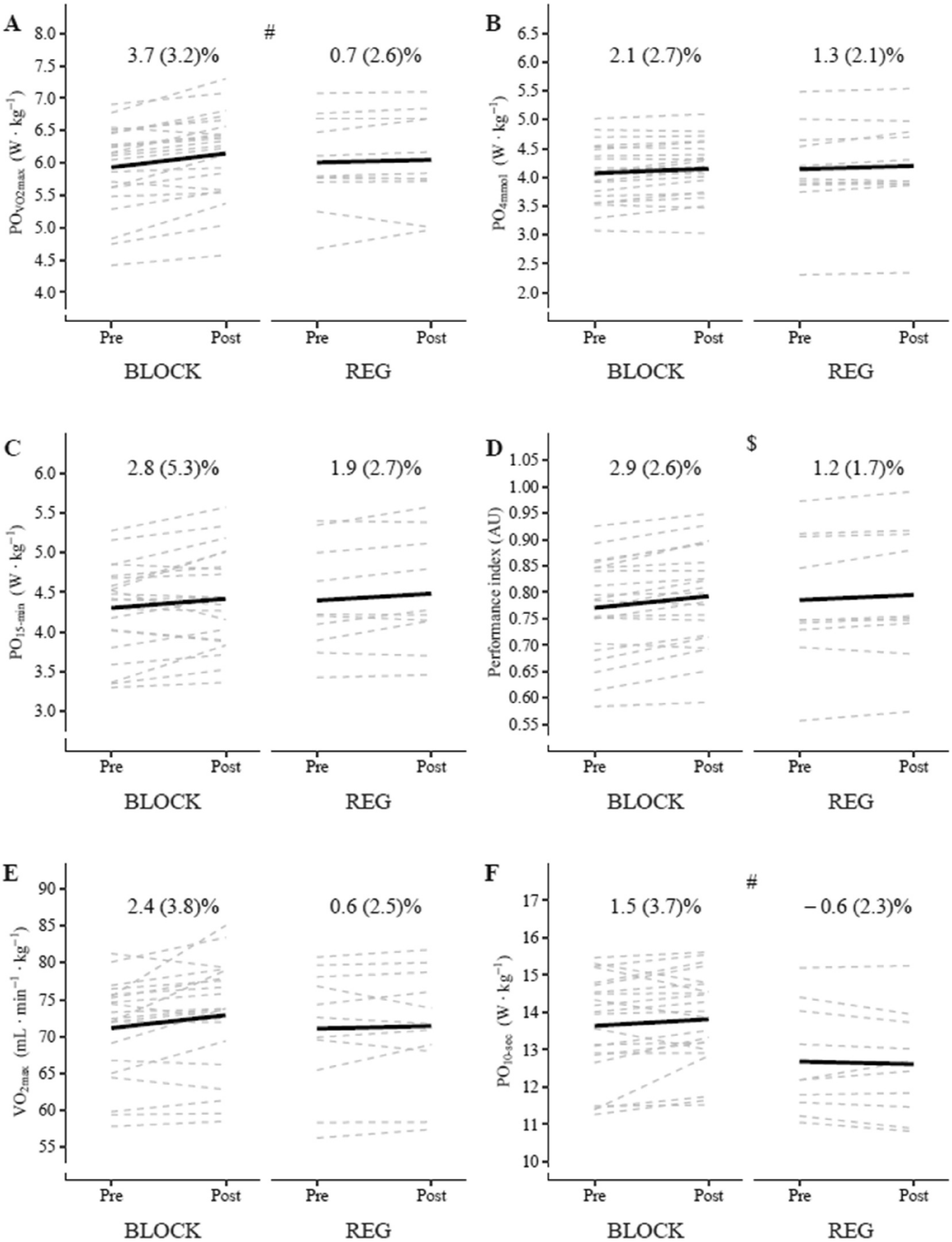

FIGURE 3 Individual data points (dotted lines) and mean values (solid lines) for (A) maximal 1-min incremental power output (PO) during the maximal oxygen consumption ($\dot{V}O_{2max}$) test ($PO_{\dot{V}O2max}$), (B) PO at 4 mmol·L^{-1} lactate concentration (PO_{4mmol}), (C) maximal average PO during the 15-min cycling trial ($PO_{15\text{-}min}$), (D) the performance index, (E) $\dot{V}O_{2max}$, and (F) 10-s mean power output ($PO_{10\text{-}sec}$), before (pre) and after (post) the high-intensity interval microcycle and the active recovery period (BLOCK) and the regular training period (REG). The values presented in each panel represent the mean (standard deviation) percentage change in the respective variables in BLOCK and REG, respectively. #Absolute change significantly greater in BLOCK compared to REG ($p \leq 0.05$). $Absolute change tends to be greater in BLOCK compared to REG ($p < 0.1$ and >0.05).

periodization of HIT is comparable to regular training in terms of improving fatigued-state endurance performance. This may imply that longer or alternative training interventions are required to enhance fatigue resistance and durability. The lack of statistical difference between groups may also be partially due to increased variability introduced by pacing strategies, despite the well-trained cyclists in this study being familiar with laboratory performance tests. Additionally, variability in fatigued-state power profiles has been shown to be greater than in fresh-state power profiles, even in professional cyclists (Spragg et al., 2023).

The novel part of this study was the use of an HIT microcycle containing HIT sessions with multiple short work intervals, which was compared to cyclists' regular training, including fewer and evenly distributed HIT sessions, as well as a greater volume of LIT. An explanation for the greater improvements in the BLOCK group may therefore be the longer accumulated and concentrated time with higher mean PO during HIT sessions compared to the REG group. The latter is verified by the tendency of longer duration of zone 5 exercise in BLOCK versus REG even though BLOCK had a reduced training load during the 6-day active recovery period. Previous research is indicative of higher upregulation of peroxisome proliferator-activated receptor gamma coactivator 1-alpha gene expression (the key regulator for mitochondrial biogenesis) in HIT performed at 100% compared with 73% of $PO_{\dot{V}O2max}$ (Edgett et al., 2013). HIT sessions with multiple short work intervals, similar to those used in the present study, have also been shown to provide more time ≥90% of $\dot{V}O_{2max}$ than longer (5-min) work intervals (Almquist et al., 2020; Rønnestad et al., 2021). Based on this, it can be suggested that the HIT microcycle with its subsequent active recovery period induced a greater training stimulus than the regular training period. Considering that a substantial exercise stimulus is typically required to induce further adaptations in already well-trained endurance athletes (Meyler et al., 2021), this may help explain the greater improvements in several of the performance indicators in BLOCK compared to REG. Interestingly, REG had a larger volume of LIT and a tendency toward a larger total TRIMP, highlighting the importance of the HIT stimulus for inducing adaptations in well-trained athletes, especially within a short time frame (Buchheit & Laursen, 2013; Laursen & Jenkins, 2002).

For changes in $\dot{V}O_{2max}$, there was a moderate ES in favor of BLOCK, but no statistically significant differences between groups. This aligns with the findings of a recent study investigating the effects of a 7-day HIT microcycle with or without adding LIT (Strepp et al., 2024) and some previous studies reporting no differences between block periodization of HIT compared to even distribution of HIT (Clark et al., 2014; McGawley et al., 2017; Rønnestad et al., 2016, 2022; Wahl et al., 2013). In contrast, several other studies have reported increased $\dot{V}O_{2max}$ after an HIT microcycle (Breil et al., 2010; Rønnestad et al., 2014b, 2021; Rønnestad & Vikmoen, 2019). The reason for the lack of increase in $\dot{V}O_{2max}$ has previously been related to the low seasonal variation in $\dot{V}O_{2max}$ observed in endurance athletes (Losnegard et al., 2013), likely caused by their high all-around training volume, including both LIT and HIT. Additionally, observations in endurance runners suggest that short-term HIT interventions minimally affect $\dot{V}O_{2max}$ changes in well-trained athletes (Denadai et al., 2006; Parmar et al., 2021; Smith et al., 2003). These outcomes highlight the challenges of improving $\dot{V}O_{2max}$ over a relatively short period of time, especially in well-trained athletes, suggesting that the improvements in endurance performance indicators in the BLOCK group were likely also related to physiological factors other than $\dot{V}O_{2max}$. In line with this, several studies involving well-trained endurance athletes have shown improvement in indicators for endurance performance without linking these enhancements to alterations in $\dot{V}O_{2max}$ (Evertsen et al., 2001; Rønnestad et al., 2016, 2022; Sandbakk et al., 2013; Wahl et al., 2013).

The finding of no difference in GE changes between groups was expected and agrees with a 10-week study investigating the effects of two weekly sessions with multiple short work intervals (Rønnestad et al., 2015). Despite an observation of improved GE after 7 days of HIT overload (Clark et al., 2014), GE is generally found to be relatively stable, evident by the observation that no changes in work economy was observed over a 6-month training period in elite cyclists (Lucía et al., 2000; Sassi et al., 2008). However, the tendency for a reduction in % of $\dot{V}O_{2max}$ at PO_{4mmol} in the BLOCK group compared with the REG group contradicts previous findings on endurance-trained athletes (Helgerud et al., 2007; Rønnestad et al., 2014b, 2016). As there were no group differences in changes in PO_{4mmol}, the importance of this tendency is likely minimal, and speculatively, it may be related to the numerically greater improvement in $\dot{V}O_{2max}$ and GE in the fresh state in BLOCK compared to REG.

4.1 | Limitations

The strength of this study was the high number of well-trained cyclists, and the use of a research design with strong ecological validity, allowing the REG group to continue with their regular training. Notably, participants were not randomized to the BLOCK and REG groups, which at one hand can be viewed as violation of the gold standard of methodological approach, while on the other hand, ensures that the participants are fully motivated for the training they are performing. Unfortunately, it is difficult to recruit well-trained athletes who will let their training content be decided by randomization. Still, it is important to be aware that the lack of randomization may introduce selection bias, as participants could differ systematically in ways that influence the outcomes. This can affect the internal validity of the findings, potentially confounding the results. Furthermore, not matching the training load between groups is a weakness of the design, potentially affecting the results. However, the calculation of total training load revealed that BLOCK reduced their total training load compared to the 2 weeks prior to the intervention, while REG had the same load during the two periods (i.e., simply continuing with their regular training). This means that BLOCK reduced their load of LIT and increased their load of HIT during the intervention, resulting in a tendency toward a lower total training load compared to REG. This distribution of training intensity and volume was as expected with the present emphasis on ecological validity (i.e., increasing HIT at the expense of LIT and total training volume and comparing it with simply continuing with the regular training stimulus). In this context, a reduction in the peak isokinetic knee-extension torque was observed in the REG group and could indicate greater muscular fatigue in this group, potentially influencing the post-intervention results. However, REG had only a reduced knee-extension torque compared to BLOCK at the low contraction velocity and not at the higher contraction velocity, which has been observed to demand longer recovery duration (Vikmoen et al., 2024; Vila-Chã et al., 2023). Furthermore, the training 2 days before testing was standardized in a similar way for both groups to ensure proper recovery before testing. Hence, the observed reduction in knee-extension torque in REG is difficult to interpret. As for the cyclists in BLOCK, it seems like they had recovered their contractile function after the 6-day HIT microcycle and 6-day active recovery period. The timing of post-intervention testing was chosen based on the design and results of a previous study (Rønnestad et al., 2022) with the aim of evaluating how HIT microcycles followed by an active recovery period can be effectively incorporated into the preparation phase of endurance training and assessing their overall efficacy, rather than to determine the optimal strategy for performance peaking. Lastly, due to the small number of female athletes, it was not feasible to investigate potential sex differences in training responses within this study.

4.2 | Practical applications

The overall goal of incorporating concentrated loads of HIT is to induce further adaptations in well-trained individuals. As the study included highly trained cyclists, the present findings indicate that a high-intensity short-interval microcycle followed by an active recovery period can improve endurance performance indicators compared with simply continuing regular training. This emphasizes the potential of such a training strategy as a valuable tool when devising endurance training programs to optimize training adaptations in well-trained endurance athletes.

5 | CONCLUSION

A 6-day HIT microcycle consisting of five short-interval training sessions with a subsequent 6-day active recovery period induces improvements in indicators of endurance performance compared with continuing regular training.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

PARTICIPANT CONSENT STATEMENT

The participants provided their written informed consent to participate in this study.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

No material from other sources is used.

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ORCID

Guro Strøm Solli https://orcid.org/0000-0002-7354-8910
Ingvill Odden https://orcid.org/0009-0005-6139-6859
Knut Sindre Mølmen https://orcid.org/0000-0001-8924-6848
Bent R. Rønnestad https://orcid.org/0000-0002-6907-1347

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