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Optimizing interval training through power output variation within the work intervals

Original Investigation

Arthur H. Bossi[1,4], Cristian Mesquida[2,4], Louis Passfield[1,3]
Bent R. Rønnestad[4], James G. Hopker[1].

[1] School of Sport and Exercise Sciences, University of Kent, Chatham, Kent, England.
[2] Facultad de Biología, Universitat de Barcelona, Barcelona, Spain.
[3] Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada.
[4] Department of Sport Science, Inland Norway University of Applied Science, Lillehammer, Norway.

Correspondence. Dr James Hopker; School of Sport and Exercise Sciences, University of Kent at Medway, Medway Building, Chatham, Kent, ME4 4AG, England; J.G.Hopker@kent.ac.uk; +44 (0)1634 888814

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ABSTRACT

Purpose. Maximal oxygen uptake ($\dot{V}O_{2max}$) is a key determinant of endurance performance. Therefore, devising high-intensity interval training (HIIT) that maximizes stress of the oxygen transport and utilization systems may be important to stimulate further adaptation in athletes. We compared physiological and perceptual responses elicited by work intervals matched for duration and mean power output, but differing in power output distribution. **Methods.** Fourteen cyclists ($\dot{V}O_{2max}$: 69.2 ± 6.6 $ml \cdot kg^{-1} \cdot min^{-1}$) completed three laboratory visits for a performance assessment and two HIIT sessions using either varied- or constant-intensity work intervals. **Results.** Cyclists spent longer time at $>90\%\dot{V}O_{2max}$ during HIIT with varied-intensity work intervals (410 ± 207 vs. 286 ± 162 s; $P = 0.02$), but there were no differences between sessions in heart rate- or perceptual-based training load metrics (all $P \geq 0.1$). When considering individual work intervals, minute ventilation ($\dot{V}E$) was higher in the varied-intensity mode ($F = 8.42$; $P = 0.01$), but not respiratory frequency, tidal volume, blood lactate concentration [La], ratings of perceived exertion, or cadence (all $F \leq 3.50$; $P \geq 0.08$). Absolute changes (Δ) between HIIT sessions were calculated per work interval, and Δ total oxygen uptake was moderately associated with $\Delta\dot{V}E$ ($r = 0.36$; $P = 0.002$). **Conclusions.** In comparison to a HIIT session with constant-intensity work intervals, well-trained cyclists sustain higher fractions of $\dot{V}O_{2max}$ when work intervals involve power output variations. This effect is partially mediated by an increased oxygen cost of hyperpnoea, and not associated with a higher [La], perceived exertion or training load metrics.

KEYWORDS. intensity prescription; time at $\dot{V}O_{2max}$; elite cycling; maximal aerobic power; exercise hyperpnoea.

INTRODUCTION

High-intensity interval training (HIIT) involves repeated bouts of high-intensity exercise interspersed with recovery periods. This method is typically employed to increase the training stimulus for the cardiorespiratory system over prolonged continuous exercise. Accordingly, much of the scientific work related to HIIT has focused on maximal oxygen uptake ($\dot{V}O_{2max}$) improvements [1-4]; as the upper limit to the aerobic metabolism and a key determinant of endurance performance [5]. It has been suggested that exercising at high intensities is beneficial to improve $\dot{V}O_{2max}$ [4], particularly in the case of well-trained athletes [1-3]. Therefore, accumulating time at or close to $\dot{V}O_{2max}$ (e.g. >90% or >95%) during a HIIT session may be important for training adaptation [1-4,6-9].

Previously, Billat et al. [10] have demonstrated that the ability to sustain exercise at >95%$\dot{V}O_{2max}$ can exceed 15 min if power output is adjusted according to expired gas responses. In comparison, constant work rate exercise or HIIT performed to exhaustion produces time at >90% or >95%$\dot{V}O_{2max}$ of only a few minutes [1-3,6,7,10]. Billat et al. [10] used a protocol that commenced at the lowest power output eliciting $\dot{V}O_{2max}$ and, once attained, power output was decreased progressively. Subsequently, power output was regulated as per individual oxygen uptake ($\dot{V}O_2$) responses, enabling >95%$\dot{V}O_{2max}$ to be sustained and time to exhaustion prolonged [10]. While this laboratory protocol is appealing as a training session, it is not practical for the majority of athletes. Alternatively, a HIIT session in which the work intervals include power output variations might provide similar means to increase time at >90%$\dot{V}O_{2max}$.

Previous research suggests that power output distribution affects physiological responses during standardized HIIT sessions [6,9], with increased time at >90%$\dot{V}O_{2max}$ following decreasing- vs. constant-intensity work intervals [6], and greater time at >85%$\dot{V}O_{2max}$ following all-out vs. constant-intensity work intervals being reported [9]. Although the aforementioned studies did not investigate potential mechanisms, authors attributed the results to a difference in $\dot{V}O_2$ kinetics between HIIT modes [6,9], as faster $\dot{V}O_2$ kinetics have been observed during decreasing- vs. constant-intensity single bouts of exercise matched for mean power output [11,12]. It is believed that $\dot{V}O_2$ kinetics reflect changes in oxidative metabolism within the muscle [13,14], which in turn respond to the energy state of the cells, in particular, the concentration of adenosine diphosphate (ADP) [15]. Higher work rates elevate ADP concentrations and activate oxidative phosphorylation more rapidly [16], ultimately producing faster $\dot{V}O_2$ kinetics at the onset of decreasing- compared to constant-intensity exercise [11,12]. This mechanism leads to the possibility that multiple changes in power output within the first half of a work interval would maximize time at >90%$\dot{V}O_{2max}$.

Despite the attractiveness of the $\dot{V}O_2$ kinetics hypothesis, ventilatory variables such as minute ventilation ($\dot{V}E$) or respiratory frequency (f_R) have been largely ignored as part of the physiological responses to different patterns of power output distribution [6,9,11,12]. As the oxygen cost of hyperpnoea at high-intensity exercise is substantial, reaching 15% of $\dot{V}O_{2max}$ in some individuals [17,18], exacerbated ventilatory responses caused by varied-intensity work intervals may help to explain an increased time at >90%$\dot{V}O_{2max}$ in this type of HIIT. Indeed, evidence suggests work rate magnitude affects ventilatory response dynamics [19]. However, the strong association reported between f_R and ratings of perceived exertion (RPE) [20] suggests the extra respiratory drive may be associated with a higher perceptual strain and premature fatigue [21], potentially offsetting the benefits of being able to spend a longer time at >90%$\dot{V}O_{2max}$.

The purpose of this study was to compare the physiological and perceptual responses elicited by work intervals matched for duration and mean power output, but differing in power output distribution. Specifically, constant-intensity work intervals were prescribed in one HIIT session, whereas power output was repeatedly varied within the work intervals of the other one. We tested the following hypotheses: higher fractions of $\dot{V}O_{2max}$ would be sustained in the varied-intensity mode, and ventilatory variables would predict changes in $\dot{V}O_2$ response.

METHODS

Participants. Fourteen well-trained male cyclists volunteered for this study during their off-season. The institution's ethics committee approved the study in compliance with the Declaration of Helsinki.

Study design. Participants visited the laboratory on three occasions, at the same time of the day, separated by at least 48 h. In the first visit, participants completed a submaximal lactate threshold test and a maximal incremental test to characterize their cycling ability and physiological profile. They were also familiarized with the HIIT sessions used during subsequent visits. In visits two and three, participants performed in randomized order two HIIT sessions with either varied- or constant-intensity work intervals, matched for duration and mean power output. Acute physiological and perceptual responses were compared between HIIT sessions at the same time points.

Participants were instructed to refrain from all types of intense exercise 24 h before each laboratory visit and to prepare as they would for competition. They were instructed to consume identical meals 1 h before each laboratory visit and to refrain from caffeine during the preceding 3 h. All tests were performed free from distractions, under similar environmental conditions (16-17°C), with participants being cooled with a fan.

Ergometer setup. All cyclists used the same bike (2017 Roubaix One.3 size 56, Fuji, Taichung, Taiwan) mounted on a cycle ergometer (KICKR, Wahoo Fitness, Atlanta, USA) considered to be valid and reliable [22,23]. Saddle position was individually adjusted and measures were noted for replication. The bike was equipped with a crank-based power meter (SRAM S975, SRM, Jülich, Germany), from which power output and cadence were recorded. An indoor cycling training software (TrainerRoad v1.0.0.49262, TrainerRoad LLC, Reno, USA) was used to customize all testing sessions, which were performed in ergometer mode. The laptop was connected to the KICKR through Bluetooth and to the SRM through an ANT+ dongle. With this setup, the resistance of the KICKR was controlled by the power output and cadence readings of the SRM. Power output, cadence and heart rate (HR) were recorded by a cycle computer (PowerControl 8, SRM, Jülich, Germany) at 1 Hz sampling rate and subsequently analyzed using GoldenCheetah v3.4. The KICKR and the SRM were calibrated by the manufacturer prior to the study. Before each use, a member of the research team warmed-up the KICKR by riding for 10 min at 100 W, and then performed the 'spindown' through the TrainerRoad software, which is a zero-offset calibration of the strain gauges based on bearing and belt friction. The zero offset procedure of the SRM was performed according to the manufacturer's recommendations.

To examine the validity of the power outputs generated by the KICKR through this setup, individual targets determined for each HIIT session (see text below) were compared to the SRM readings. A freely available spreadsheet [24] was used to assess data at 77%, 84% and 100% of maximal aerobic power (MAP) for agreement, with a total of 288, 96 and 288 duplicates, respectively. The comparison KICKR vs. SRM revealed a typical error of estimate (TTE) of 7 W [CL: 6 – 7 W], correlation coefficient (r) of 0.98 [CL: 0.97 – 0.98] and mean bias of -3 W [CL: -4 – -3 W] at 77%MAP; a TEE of 2 W [CL: 2 – 3 W], r = 1.00 [CL: 1.00 – 1.00] and mean bias of 1 W [CL: 0 – 1 W] at 84%MAP; and a TEE of 8 W [CL: 7 – 9 W], r = 0.97 [CL: 0.97 – 0.98] and mean bias of 11 W [CL: 10 – 12 W] at 100%MAP. Our ergometer setup was therefore deemed valid.

Preliminary testing. In the first visit, participant's height and body mass were measured and they completed a cycling experience index questionnaire [25], as well as standalone questions about their training habits. Briefly, by adding up the scores from each question, individuals are assigned a total score from 0 (representing a complete non-cyclist) to 37 (representing a highly experienced and well-trained cyclist) [25]. Participants subsequently completed a lactate threshold test, which started at 125 W, increasing by 50 W every fifth minute (25 W if blood lactate concentration [La] was $\geq$ 3 mmol·L^{-1}), and terminated when [La] reached $\geq$ 4 mmol·L^{-1}. Blood samples were taken from a fingertip at the last 30 s of each 5-min bout and were immediately analyzed (Biosen C-Line, EKF Diagnostics, Penarth, UK). At the start of the test, cyclists chose their cadence, which they subsequently held constant throughout the remainder of the test. Power output at 4 mmol·L^{-1} [La] was calculated for each cyclist from the relationship between [La] and power output in the last two stages, by using linear regression. $\dot{V}O_2$ was measured during the last 3 min of each stage (15-s sampling time) using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). Prior to every test, the gas analyzer was calibrated with certified calibration gases of known concentrations and the flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was calibrated with a 3 L syringe (5530 series, Hans Rudolph, Kansas City, USA).

After the lactate threshold test, cyclists rode for 10 min at a power output between 50 and 100 W before performing the maximal incremental test to determine both $\dot{V}O_{2max}$ and MAP. The test started at 200 W with work rate being increased by 25 W every minute until voluntary exhaustion, or an inability to maintain cadence above 70 rev·min^{-1} despite verbal encouragement. Pedaling cadence was freely chosen but participants were instructed to avoid abrupt changes. $\dot{V}O_2$ was continually measured, and $\dot{V}O_{2max}$ was calculated as the highest 60-s mean. MAP was calculated according to Daniels et al. [26]. This method extrapolates the relationship between submaximal power outputs and respective measures of $\dot{V}O_2$ to $\dot{V}O_{2max}$, by means of linear regression [26]. Power output data were recorded continuously throughout the test, with $\dot{W}_{max}$ calculated as the mean of the last 60-s of the incremental test. Straight after the incremental test, a blood sample was taken from a fingertip and immediately analyzed to establish [La]. Cyclists reported their peak RPE using the Borg's 6-20 scale immediately after terminating the test.

HIIT sessions. Initially, participants performed a 15-min warm-up based on Borg's 6-20 RPE scale. The warm-up consisted of 5 min at 11 (light), followed by three 1-min intervals at 16 (between hard and very hard), interspersed with two 2-min blocks, and a final 3 min, all at 9 (very light). Cyclists were allowed to manipulate the work rate imposed by the cycle ergometer in order to match the required RPE.

Both HIIT sessions started with 5 min at 50%MAP, followed by six 5-min work intervals at a mean intensity of 84%MAP, interspersed with 2.5-min recovery at 30%MAP. Varied-intensity work intervals consisted of three 30-s surges at 100%MAP, interspersed with two 1-min blocks, and a final 1.5 min at 77%MAP. Constant-intensity work intervals consisted of 5 min at 84%MAP. A detailed outline of the warm-up and both work intervals can be seen in Figure 1. The number of work intervals, their duration, and the duration of recovery intervals were chosen based on athletes perception of what constitutes a valuable training session for aerobic capacity development. The mean intensity for the work intervals was chosen based on pilot testing to warrant both HIIT sessions would be completed with physiological responses typical of exercise performed within the severe intensity domain. As for the varied-intensity work intervals, the 30-s surges at 100%MAP were chosen based on previous work of our lab with cyclists [7] and cross-country skiers [27]. Given the superior time at >90%$\dot{V}O_{2max}$ elicited by 30-s compared to longer work intervals in the cycling study [7], we reasoned that the 1.5 min at 100%MAP employed in the cross-country skiing study [27] could be split into three surges to characterize the varied-intensity work interval.

HR was continuously measured during the entire HIIT sessions. $\dot{V}O_2$ was measured during the 5-min work intervals (5-s sampling time) using the same equipment and following the calibration procedures adopted in the preliminary testing. Time at >90%$\dot{V}O_{2max}$ was calculated by summing all raw $\dot{V}O_2$ measures over the established cut-off. At the end of each work interval, fingertip blood samples were taken to assess [La], and RPE was recorded. Participants self-selected their cadence and water consumption was not restricted. Twenty minutes after finishing the HIIT sessions, session RPE (sRPE) was recorded. iTRIMP, a training-load metric based on HR [28], was also calculated to compare the training load between HIIT sessions. Within the iTRIMP calculation, exercise intensity is weighted according to participants' own HR–[La] exponential relationship [28], obtained during the preliminary testing. iTRIMP was calculated for each HIIT session by summing the weighted scores from every 5-s HR means [28].

[Figure 1 here]

Data analyses. Dependent variables were assessed for normality using Shapiro-Wilk tests. Paired t-tests were used to compare time at >90%$\dot{V}O_{2max}$, sRPE and iTRIMP between HIIT sessions. Two-way repeated measures analyses of variance (work interval mode x work interval number) were performed to test for differences in mean $\dot{V}O_2$ as a percentage of maximal (%$\dot{V}O_{2max}$), total $\dot{V}O_2$, mean $\dot{V}E$, mean ventilatory equivalent for oxygen ($\dot{V}E \cdot \dot{V}O_2^{-1}$), mean f_R, mean tidal volume (V_T), mean carbon dioxide output ($\dot{V}CO_2$), mean HR, [La], RPE, and mean cadence. Following analysis of variance, Bonferroni pairwise comparisons were used to identify where significant differences existed within the data. Cohen d or partial eta squared (η^2_p) were computed as effect size estimates. Absolute changes between HIIT sessions were calculated for mean $\dot{V}E$ ($\Delta\dot{V}E$) and total $\dot{V}O_2$ ($\Delta\dot{V}O_2$) per work interval. The association between $\Delta\dot{V}E$ and $\Delta\dot{V}O_2$ was modelled by multilevel analysis with participant as a random effect (i.e. random intercept). A correlation coefficient (r) was then computed by adjusting for repeated observations within participants. Data were analyzed using SSPS (SSPS Statistics 25, IBM, Armonk, USA) and significance level was set at $P \leq 0.05$. Results are presented as mean ± SD [90% confidence limits (CL)].

RESULTS

Participants' characteristics are presented in Table 1. There was a longer time at >90%$\dot{V}O_{2max}$ for HIIT with varied- compared to constant-intensity work intervals (410 ±

207 vs. 286 ± 162 s [CL: 312 – 508 vs. 209 – 362 s]; $t = 2.63$; $P = 0.02$; $d = 0.16$ – Figure 2a), despite no difference in mean power output as measured by the SRM crank (324 ± 30 vs. 323 ± 30 W [CL: 310 – 338 vs. 309 – 337 W]; $t = 1.35$; $P = 0.20$; $d = 0.01$). There was also no differences in sRPE (6.0 ± 1.8 vs. 6.6 ± 1.7 [CL: 5.2 – 6.9 vs. 5.8 – 7.5]; $t = -1.62$; $P = 0.13$; $d = -0.09$ – Figure 2b), or iTRIMP (178 ± 43 vs. 181 ± 46 [CL: 157 – 198 vs. 160 – 203]; $t = -0.43$; $P = 0.68$; $d = -0.02$ – Figure 2c). The mean $\dot{V}O_2$ responses to both types of work intervals are presented in Figure 3.

[Table 1 here]
[Figure 2 here]
[Figure 3 here]

Statistics and effect size estimations from the analysis of variance are given in Table 2. No interactions between work interval mode and work interval number were found for $\%\dot{V}O_{2max}$ (Figure 4a), total $\dot{V}O_2$ (Figure 4b), $\dot{V}E$ (Figure 4c), $\dot{V}E \cdot \dot{V}O_2^{-1}$, f_R (Figure 4d), V_T (Figure 4e), $\dot{V}CO_2$ (Figure 4f), HR, [La] (Figure 4g), RPE (Figure 4h), or cadence (Figure 4i). There was a main effect of work interval mode for $\%\dot{V}O_{2max}$, total $\dot{V}O_2$, $\dot{V}E$, $\dot{V}E \cdot \dot{V}O_2^{-1}$ and $\dot{V}CO_2$, but not for f_R, V_T, HR, [La], RPE, or cadence. A main effect of work interval number was found for $\%\dot{V}O_{2max}$, total $\dot{V}O_2$, $\dot{V}E$, $\dot{V}E \cdot \dot{V}O_2^{-1}$, f_R, V_T, HR, [La] and RPE. Pairwise comparisons revealed differences between consecutive work intervals for all variables (all $P \leq 0.05$), except for V_T, in which work interval 1 was different from 3, 4, 5 and 6 (all $P \leq 0.02$). There was no main effect of work interval number for $\dot{V}CO_2$ or cadence.

[Table 2 here]
[Figure 4 here]

Multilevel analysis produced the following model ($y = mx + b$):

$$\Delta\dot{V}O_2\,(\text{ml}) = 23.3 \cdot \Delta\dot{V}E\,(\text{L}\cdot\text{min}^{-1}) + 239.6 \qquad (1)$$

($m_{SE} = 4.4$; $P < 0.001$; $b_{SE} = 118.9$; $P = 0.06$; ICC = 0.43)

A moderate correlation was found between $\Delta\dot{V}E$ and $\Delta\dot{V}O_2$ ($r = 0.36$; $r^2 = 0.13$; $P = 0.002$).

DISCUSSION

Consistent with our first hypothesis, well-trained cyclists sustained higher fractions of $\dot{V}O_{2max}$ when they performed the varied- compared to constant-intensity work intervals during a HIIT session. Time at $>90\%\dot{V}O_{2max}$, $\%\dot{V}O_{2max}$ sustained, and total $\dot{V}O_2$, all suggest an increased aerobic cost elicited by the varied-intensity work intervals. Importantly, this increased demand was not accompanied by a higher f_R, HR, [La], RPE, or cadence. Furthermore, we found no differences between conditions in sRPE or iTRIMP, which may suggest varied-intensity work intervals produce a higher training stimulus per dose of exercise. Consistent with our second hypothesis, $\dot{V}E$ was also higher during the varied- compared to constant-intensity work intervals. In addition, $\Delta\dot{V}E$ was moderately associated with $\Delta\dot{V}O_2$, suggesting differences in the oxygen cost of hyperpnoea partially explain the magnitude of $\dot{V}O_2$ differences between HIIT sessions.

Varying power output between 100% and 77%MAP within the work intervals of a HIIT session increased the mean time at $>90\%\dot{V}O_{2max}$ by 43%, from 286 s (4 min 46 s) produced by the constant-intensity work intervals (84%MAP) to 410 s (6 min 50 s). This result stands out as we did not manipulate the mean intensity and length of the work and recovery intervals, or total HIIT duration, which often is the case in studies assessing time at or close to $\dot{V}O_{2max}$ [1-3,7,8]. Previously, Billat et al. [10] demonstrated that effort could be minimized, and exercise sustained for more than 15 min at >95%$\dot{V}O_{2max}$, when power output was manipulated according to expired gas responses. Despite HIIT with varied-intensity work intervals produced a shorter duration at >90%$\dot{V}O_{2max}$ compared to that of Billat et al. [10], our results provide evidence for a more practical approach to programming this type of training.

Unique to our study was that varied-intensity work intervals increased $\dot{V}O_2$ without affecting most variables reflecting the physiological and perceptual strain of exercise. In contrast, Zadow et al. [9] reported times at >85%$\dot{V}O_{2max}$ of 2 min 31 s and 2 min 04 s, for respectively all-out and constant-intensity work intervals, but with greater HR, RPE, and sRPE [9]. Collectively, these results suggest there may be a tolerance limit for the magnitude of power output variation that allows cyclists to optimize time at >90%$\dot{V}O_{2max}$ without compromising exercise capacity. Another strength of our work is that HIIT sessions were matched for all prescription elements affecting the exercise dose, except power output distribution. For instance, Lisbôa et al. [6] reported longer time at >90%$\dot{V}O_{2max}$ (4 min 19 s vs. 2 min 03 s) following decreasing- vs. constant-intensity work intervals, but conditions were matched by participant’s capacity to perform work above critical power [6]. Work and recovery interval durations were not controlled, potentially affecting time at a high fraction of $\dot{V}O_{2max}$ more than the power output distribution itself [1-3,7,8]. Thus, the higher time at >90%$\dot{V}O_{2max}$ was likely achieved by a change in exercise dose.

HIIT can be prescribed with different formats according to the aim of the training session. To produce the longest times at or close to $\dot{V}O_{2max}$, short work intervals (< 1 min) have been recommended [1-3,7,8]. In agreement with this proposition, adding repeated power output variations within longer 5-min work intervals increased time at >90%$\dot{V}O_{2max}$. Nevertheless, there is contrasting evidence from training studies, with evidence that both short [8,29] and long work intervals [4,30] may trigger a potent stimulus for increasing $\dot{V}O_{2max}$. This suggests time at >90%$\dot{V}O_{2max}$ is unlikely to be the only training variable driving $\dot{V}O_{2max}$ enhancements. Its relatively poor reliability must also be taken into account [31]. Despite these considerations, we speculate that our novel HIIT session, if repeated over time, may combine the benefits of both short and longer work intervals. Further work is necessary to confirm this hypothesis.

Ventilatory responses to work intervals of different power output distributions have been previously neglected [6,9]. Interestingly, our results suggest they play a role in the observed changes in total $\dot{V}O_2$. Compared to constant-intensity work intervals, varied intensity produced higher $\dot{V}E$ and $\dot{V}E\cdot\dot{V}O_2^{-1}$, implying a greater mechanical work of the pulmonary system and an increased oxygen cost of hyperpnoea [17,18,32]. Indeed, the multilevel analysis used in this study predicted that for each L of increase in $\dot{V}E$, $\dot{V}O_2$ is increased by 4.7 ml. This is nevertheless higher than the cost of exercise hyperpnoea reported by Aaron et al. [32] as 2.9 ml of oxygen per L of $\dot{V}E$, or more recently by Dominelli et al. [18] as 2.4 ml·L^{-1}. Taking together the model intercept of 239.6 ml, results suggest mechanisms other than an increased $\dot{V}E$ may account to a greater extent for the observed changes in aerobic cost of HIIT. It is therefore not surprising that only a moderate correlation between $\Delta\dot{V}E$ and $\Delta\dot{V}O_2$ (r = 0.36) was found in the present study.

The fact we did not find differences in f_R or V_T between varied- and constant-intensity work intervals, alongside the differences in $\dot{V}E$, has some practical and mechanistic implications. Practically, f_R has been considered a marker of physical effort [20], reinforcing the sense of equivalence in strain levels between both types of HIIT. Mechanistically, a higher $\dot{V}E$ with no significant changes in either f_R or V_T indicates that both contributed to the increases in $\dot{V}E$, although in small magnitudes or with inter-individual differences, challenging the hypothesis of a distinct mechanistic control of f_R and V_T during exercise [20]. Indeed, it has been previously suggested that during high-intensity exercise central command regulates $\dot{V}E$ preferentially through changes in f_R [20], which our data do not support. Instead, Tipton et al. [33] have proposed $\dot{V}E$ is regulated by a complex integration of mechanical and physiological factors, making it difficult to completely associate f_R and V_T with a particular type of reflex. Therefore, the higher $\dot{V}E$ in the varied- compared to the constant-intensity work intervals is likely the result of a tightly coupled interaction between the increases in f_R and V_T that manifest during this type of exercise.

Additional mechanistic insight can be gained from a close inspection of Figure 3. Repeated surges at 100%MAP, as opposed to a single surge at the start of each work interval, seem required to produce the observed differences in time at $>90\%\dot{V}O_{2max}$. Not only the oxygen cost of hyperpnoea, but also the oxygen cost of muscle contraction, may have been greater during the varied- compared to the constant-intensity work intervals. Higher exercise intensities have been shown to elicit a more uniform activation of the quadriceps femoris muscles [34] and their motor units [34,35]. Thus, it is reasonable to assume some high-threshold fibers were only recruited at 100%MAP. The low efficiency and high fatigability of these fibers may have contributed to an increased whole-body $\dot{V}O_2$ and time at $>90\%\dot{V}O_{2max}$ [13]. Besides, we cannot discard the $\dot{V}O_2$ kinetics hypothesis as proposed by other authors [6,9,11,12]. If the initial 30-s surges of the varied-intensity work intervals did not directly affect time at $>90\%\dot{V}O_{2max}$, faster $\dot{V}O_2$ kinetics apparently contributed to a higher $\%\dot{V}O_{2max}$ sustained and total $\dot{V}O_2$. Future studies should use breath-by-breath ergospirometry and leg electromyography to provide evidence for these hypotheses.

PRACTICAL APPLICATIONS

Well-trained cyclists looking for alternative strategies to optimize training stimulus are advised to try the varied-intensity work intervals as outlined here. Whether performance adaptations will be superior to constant-intensity work intervals remains to be stablished by a longitudinal study; but similar f_R, HR, [La], RPE and training load metrics suggest it is unlikely that negative training outcomes occur.

CONCLUSIONS

In comparison to a HIIT session with constant-intensity work intervals, well-trained cyclists sustain higher fractions of $\dot{V}O_{2max}$ when power output is repeatedly varied within the work intervals. This effect is partially mediated by an increased oxygen cost of hyperpnoea.

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FIGURE CAPTIONS

Fig. 1 a. Warm-up procedure based on ratings of perceived exertion (RPE) that was performed prior to both sessions of high-intensity interval training (HIIT), b. varied-intensity work intervals, c. constant-intensity work intervals. The intensity of both sessions was prescribed as a percentage of the individual's maximal aerobic power (%MAP) and six work intervals were completed. Both HIIT sessions started with 5 min at 50%MAP, which is omitted from the figure for clarity.

Fig. 2 a. Time spent over 90% of maximal oxygen uptake (time at >90%$\dot{V}O_{2max}$), b. session ratings of perceived exertion (sRPE), c. training load metric based on heart rate (iTRIMP). Open circles represent each participant and black squares represent the mean values for high-intensity interval training sessions with varied- (varied WI) and constant-intensity work intervals (constant WI). *Different from constant WI ($P = 0.02$).

Fig. 3 Mean oxygen uptake ($\dot{V}O_2$) responses (5-s sampling time) to varied- (dotted line) and constant-intensity (solid line) work intervals. The horizontal dashed line represents 90% of maximal oxygen uptake (mean of all participants). SD is omitted from the figure for clarity. As individual participants reached 90% of maximal oxygen uptake at different time points, dotted and solid lines do not reflect the mean time spent over 90% of maximal oxygen uptake.

Fig. 4 a. Mean oxygen uptake as a percentage of maximal (%$\dot{V}O_{2max}$), b. total oxygen uptake (Total $\dot{V}O_2$), c. mean minute ventilation ($\dot{V}E$), d. mean breathing frequency (f_R), e. mean tidal volume (V_T), f. mean carbon dioxide output ($\dot{V}CO_2$), g. blood lactate concentration [La], h. ratings of perceived exertion (RPE), i. mean cadence. Data are displayed per work interval as mean ± SD for high-intensity interval training sessions with varied- (triangles) and constant-intensity work intervals (squares). *Different from previous work interval (all $P \leq 0.03$). †Different from work intervals 3, 4, 5 and 6 (all $P \leq 0.02$). ‡Main effect of work interval mode (all $P \leq 0.01$). §Main effect of work interval number (all $P < 0.001$).