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# The Acute Physiological and Perceptual Effects of Individualizing the Recovery Interval Duration Based Upon the Resolution of Muscle Oxygen Consumption During Cycling Exercise

**Christopher R.J. Fennell and James G. Hopker**

***Purpose:*** There has been paucity in research investigating the individualization of recovery interval duration during cycling-based high-intensity interval training (HIIT). The main aim of the study was to investigate whether individualizing the duration of the recovery interval based upon the resolution of muscle oxygen consumption would improve the performance during work intervals and the acute physiological response of the HIIT session, when compared with a standardized (2:1 work recovery ratio) approach. ***Methods:*** A total of 16 well-trained cyclists (maximal oxygen consumption: 60 [7] mL·kg$^{-1}$·min$^{-1}$) completed 6 laboratory visits: (Visit 1) incremental exercise test, (Visit 2) determination of the individualized (IND) recovery duration, using the individuals' muscle oxygen consumption recovery duration to baseline from a 4- and 8-minute work interval, (Visits 3–6) participants completed a 6 × 4- and a 3 × 8-minute HIIT session twice, using the IND and standardized recovery intervals. ***Results:*** Recovery duration had no effect on the percentage of the work intervals spent at >90% and >95% of maximal oxygen consumption, maximal minute power output, and maximal heart rate, during the 6 × 4- and 3 × 8-minute HIIT sessions. Recovery duration had no effect on mean work interval power output, heart rate, oxygen consumption, blood lactate, and rating of perceived exertion. There were no differences in reported session RPE between recovery durations for the 6 × 4- and 3 × 8-minute HIIT sessions. ***Conclusion:*** Individualizing HIIT recovery duration based upon the resolution of muscle oxygen consumption to baseline levels does not improve the performance of the work intervals or the acute physiological response of the HIIT session, when compared with standardized recovery duration.

***Keywords:*** high-intensity interval training, recovery prescription, near-infrared spectroscopy, time at $VO_2$max

High-intensity interval training (HIIT) programming comprises of 5 main components: work interval intensity, work interval duration, number of work intervals, recovery interval intensity, and recovery interval duration.[1] The work interval components have received the greatest amount of research attention as they ultimately facilitate the majority of the training stimulus produced by the HIIT session.[1] However, optimal HIIT session performance (ie, achieving the greatest training stimulus for the specific HIIT session) can only be achieved if adequate recovery separates the work intervals. If there is an imbalance between the demands of the work interval and the recovery provided, this can lead to HIIT sessions that are too hard to complete[2] or HIIT sessions that are too easy.[3]

Surprisingly, despite the importance of the recovery interval duration to HIIT session programming, there has been paucity of research investigating the effect of recovery interval duration on subsequent work interval performance. Previous researchers investigating the acute effects of recovery interval duration have predominantly used fixed recovery durations and/or work recovery ratios (ie, 1:1 or 2:1) to prescribe recovery interval duration.[3–7] While fixed durations and work recovery ratios might be the most common and practical approach to prescribing recovery interval duration, it is based upon the assumption that every individual requires the same recovery duration during HIIT sessions. On the contrary, the optimal duration is most likely highly individual, dependent on training status and desired session outcome.[6] Researchers have attempted to use self-selected recovery durations as a method of individualization demonstrating the method to be effective when participants are well familiarized with the procedures and physical demands of the HIIT protocol.[4,5,8–10] While self-selected recovery durations take into consideration the day-to-day variation in the individuals environmental and/or psychological state,[8,10,11] it does not take into account the individuals' recovery status in order to recommence exercise. If the individual's physiological status during recovery is not considered, it could lead to inadequate or excessive recovery between work intervals, potentially compromising the training session.

The use of heart rate (HR) is a physiologically based method to individualize the duration of the recovery interval.[10] However, the method has received limited research attention, which is most likely due to the inherent limitations of using HR to prescribe recovery duration.[5,12–14] More recently, the $W'_{BAL}$ model has been proposed as a method to individualize interval training.[15] For example, when working at intensities above the critical power, a cyclist would deplete the finite energy capacity defined by W', and in recovery below critical power, W' would replenish over time. During intermittent exercise, the balance of W' remaining has been suggested to predict an athlete's interval training capacity, accounting for both the work and recovery elements of a given training prescription. However, the robustness of $W'_{BAL}$ has been questioned.[16]

Near-infrared spectroscopy (NIRS) is a well-known noninvasive method used to measure muscle oxygenation, which reflects the ratio of oxygen ($O_2$) delivery to the working muscle and muscle oxygen uptake in the capillary beds.[17] The recovery of muscle oxygen consumption ($m\dot{V}O_2$) considers the condition of the exercising muscle, as measurements are derived directly from

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the muscle body. It has been suggested that the recovery duration of m$\dot{V}O_2$ after high-intensity exercise is likely related to a greater depletion of adenosine triphosphate , phosphocreatine (PCr), and/or myoglobin $O_2$ stores, which logically take longer to be restored. In addition, it is possible that m$\dot{V}O_2$ remains elevated above baseline values after high-intensity exercise to compensate for the detrimental effect of a decreased muscle pH on PCr recovery.[18,19] Therefore, it is possible that m$\dot{V}O_2$ recovery coincides with the return of the exercising muscle to a state of metabolic homeostasis. The recovery rate of m$\dot{V}O_2$ also takes into account the intensity of the prior exercise,[20] the individual's training status,[21,22] and age.[23] Based on the previously mentioned evidence, current authors propose that the recovery duration of m$\dot{V}O_2$ may provide a method to individualize HIIT recovery interval duration.

The current study therefore sought to investigate whether individualizing the duration of the recovery interval based on the participants individualized (IND) m$\dot{V}O_2$ recovery duration to baseline would improve the performance of self-paced work intervals and the acute physiological response when compared with a standardized recovery duration (STD; 2:1 work recovery ratio). It was hypothesized that the IND recovery duration would increase work interval power output (PO) resulting in a greater acute physiological response during the work intervals when compared with the STD recovery duration.

# Methods

## Participants

A total of 16 trained cyclists with a minimum of 2 years of competitive racing experience participated in the study. The study was completed with full ethical approval from the University of Kent, according to the Declaration of Helsinki standards. All participants provided signed informed consent prior to testing.

## Study Design

Each participant completed 6 visits to the laboratory. Visit 1 was an incremental exercise test to identify $\dot{V}O_2$max and to familiarize the participants with the laboratory environment. Visit 2 was the determination of the participants' IND recovery duration. In Visits 3 to 6, participants performed 4 HIIT sessions in a randomized order within 2 weeks.

Visits were conducted on nonconcurrent days, and participants were instructed to refrain from any exercise in the day prior to testing and intense exercise in the 2 days prior. Participants were instructed not to consume caffeine within 4 hours and alcohol within 24 hours of testing, and to arrive euhydrated, having eaten at least 4 hours prior to testing. Participants completed all their visits at the same time of day to avoid any circadian variance.

Participants used their own bike at all visits, affixed to a Cyclus2 ergometer (RBM elektronik-automation GmbH, Leipzig, Germany). At all visits, respiratory gas exchange data were assessed using breath by breath gas analysis (Metalyzer 3B; CORTEX Biophysik GmbH, Leipzig, Germany). Prior to all testing, the analyzer was calibrated according to the manufacturer's recommendations.

## Incremental Exercise Test

The $\dot{V}O_2$max test protocol started with a 10-minute warm-up at 100 W, after which the required cycling PO was increased by

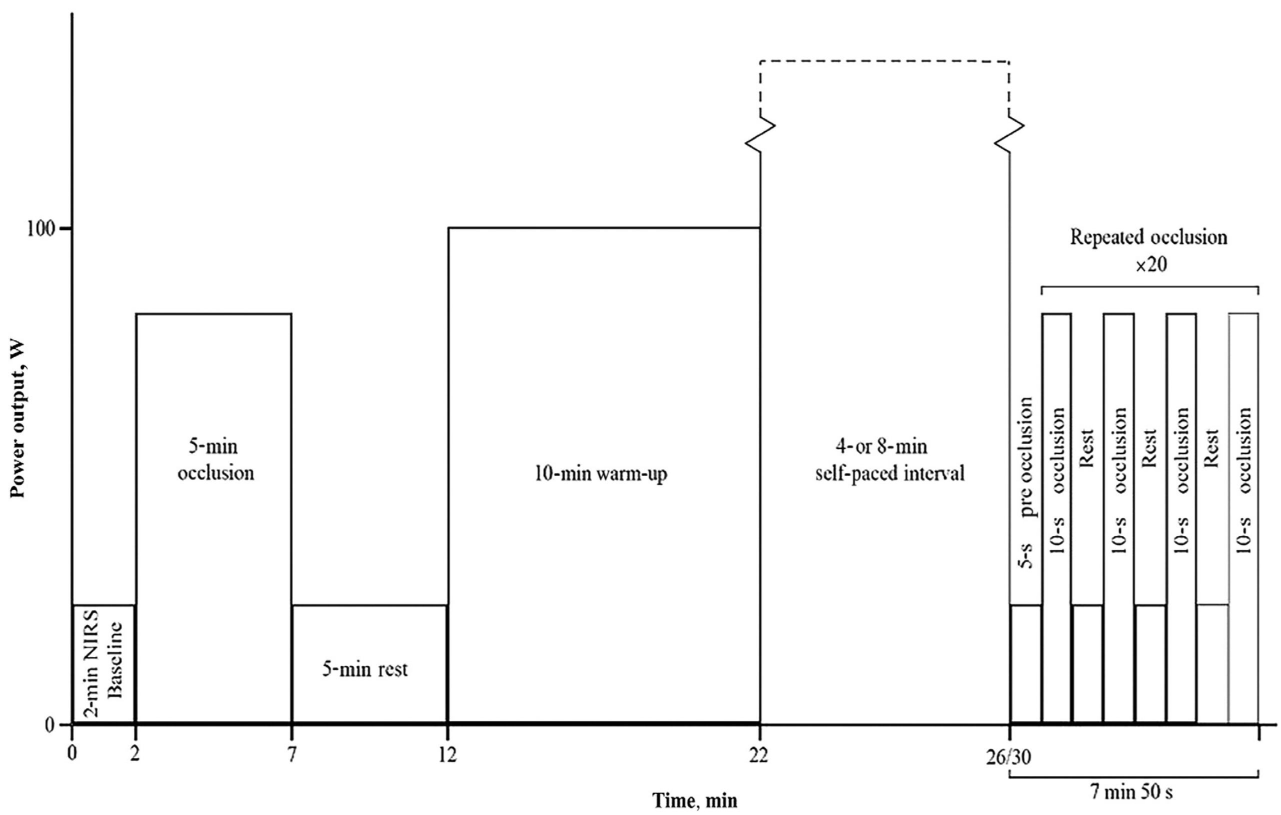


**Figure 1** — Schematic of repeated occlusion protocol for the determination of m$\dot{V}O_2$ recovery duration. m$\dot{V}O_2$ indicates muscle oxygen consumption; NIRS, near-infrared spectroscopy.

20 W every 1 minute until volitional exhaustion. The PO and HR were measured continuously throughout the test, with a rating of perceived exertion (RPE) taken in the last 10 seconds of each 1-minute stage of the test, using the Borg 6 to 20 scale.[24] The participant's $\dot{V}O_2max$ was assessed as the highest pulmonary $O_2$ uptake that was attained during a 1-minute period. Maximal minute power (MMP) and maximal minute heart rate ($HR_{max}$) were assessed as the highest 1 minute PO and HR achieved during the test.

## Methods for the Determination of $m\dot{V}O_2$ Recovery Duration

The NIRS data were acquisitioned at 10 Hz from the right vastus lateralis muscle (approximately 8 cm from the knee joint on the vertical axis) using a continuous-wave NIRS device (PortaMon, Artinis Medical Systems, Einsteinweg, The Netherlands). Skinfold thickness at the site of application of the NIRS optode was determined before the session using Harpenden Skinfold Caliper (British Indicators Ltd, Burgess Hill, United Kingdom). A rapid inflating blood pressure cuff (Hokanson E20 cuff inflator, SC12 cuff; D. E. Hokanson, Inc, Bellevue, WA) was placed around the thigh proximal to the NIRS device.

Prior to the commencement of the exercise, participants adopted a standardized resting position, seated with the knee flexed at 90° for a 2-minute period, during which baseline NIRS parameters were established. A 5-minute ischemic calibration procedure was then performed to scale the NIRS oxyhemoglobin and deoxyhemoglobin (HHb) signals to the maximal physiological range.[25] After warming up at 100 W for 10 minutes, the participants completed a single self-paced 4-minute interval. Immediately (5 s) following the interval, a series of 20 brief (ie, 10 s) arterial occlusions were applied to measure $m\dot{V}O_2$ recovery.[25] Participants were instructed to keep the leg under occlusion at the bottom of the pedal stroke, remaining completely still and to hold the same posture throughout the occlusion procedure. After cooling down at 100 W for 10 minutes, participants then completed a seated rest for 20 minutes before repeating the previously mentioned protocol; this time completing a single self-paced 8-minute interval (Figure 1).

A blood volume correction was applied to the NIRS data prior to the calculation of $m\dot{V}O_2$.[25] The $m\dot{V}O_2$ was calculated as the initial slope of change in corrected HHb during the arterial occlusion using simple linear regression. The linear slope of increase in corrected HHb expressed in micromolar units was converted to milliliters $O_2$ per minute per 100 g tissue ($mL\cdot O_2\cdot min^{-1}\cdot 100\ g^{-1}$) using the following equation.[26]

$$m\dot{V}O_2 = [(HHb \times 60)/(10 \times 1.04) \times 4] \times 22.4/1000 \qquad (1)$$

Data derived from the repeated arterial occlusions were then plotted versus recovery time to show the time course of $m\dot{V}O_2$ recovery after the 4- and 8-minute intervals (Figure 2A). The participant's IND recovery duration was calculated as the time at which the $m\dot{V}O_2$ recovery curve intercepts the 95% $m\dot{V}O_2$ value output from equation 2 (Figure 2A). A 95% $m\dot{V}O_2$ value was used to ensure a plateau in $m\dot{V}O_2$ was reached, taking into account differences in the rate of $m\dot{V}O_2$ recovery and allowing for easy replication across participants. The 95% $m\dot{V}O_2$ value was calculated as 95% of the difference between the peak $m\dot{V}O_2$ value and the end $m\dot{V}O_2$ value (equation 2).

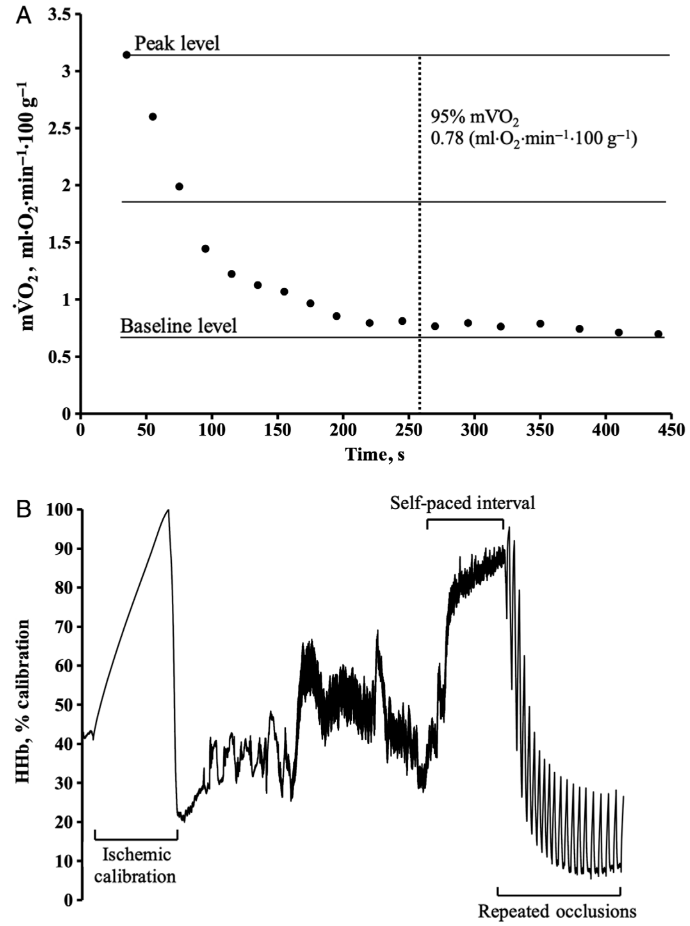


**Figure 2** — (A) Example of $m\dot{V}O_2$ recovery curve. In this example, the 95% $m\dot{V}O_2$ value output from equation (1) was 0.78 ($mL\cdot O_2\cdot min^{-1}\cdot 100\ g^{-1}$). The time point at which the $m\dot{V}O_2$ curve intercepted 0.78 ($mL\cdot O_2\cdot min^{-1}\cdot 100\ g^{-1}$) provides the IND recovery duration (ie, 260 s). (B) Complete HHb trace from determination of $m\dot{V}O_2$ recovery duration protocol. HHb indicates deoxyhemoglobin; IND, recovery duration to baseline; $m\dot{V}O_2$, muscle oxygen consumption.

$$m\dot{V}O_2value = \left((m\dot{V}O_2peak - m\dot{V}O_2end) - \left(\frac{(m\dot{V}O_2peak - m\dot{V}O_2end)}{100} \times 95\right)\right) + m\dot{V}O_2end \qquad (2)$$

where $m\dot{V}O_2peak$ = first $m\dot{V}O_2$ value following the first cuff inflation and $m\dot{V}O_2end$ = last $m\dot{V}O_2$ value at the end of the measurement period.

## HIIT Sessions

Participants completed both the 6 × 4- and 3 × 8-minute HIIT sessions twice (4 HIIT sessions in total), once with the STD recovery duration and once with the IND recovery duration (Figure 3). The STD recovery durations used were 120 and 240 seconds for the 6 × 4- and 3 × 8-minute HIIT sessions,

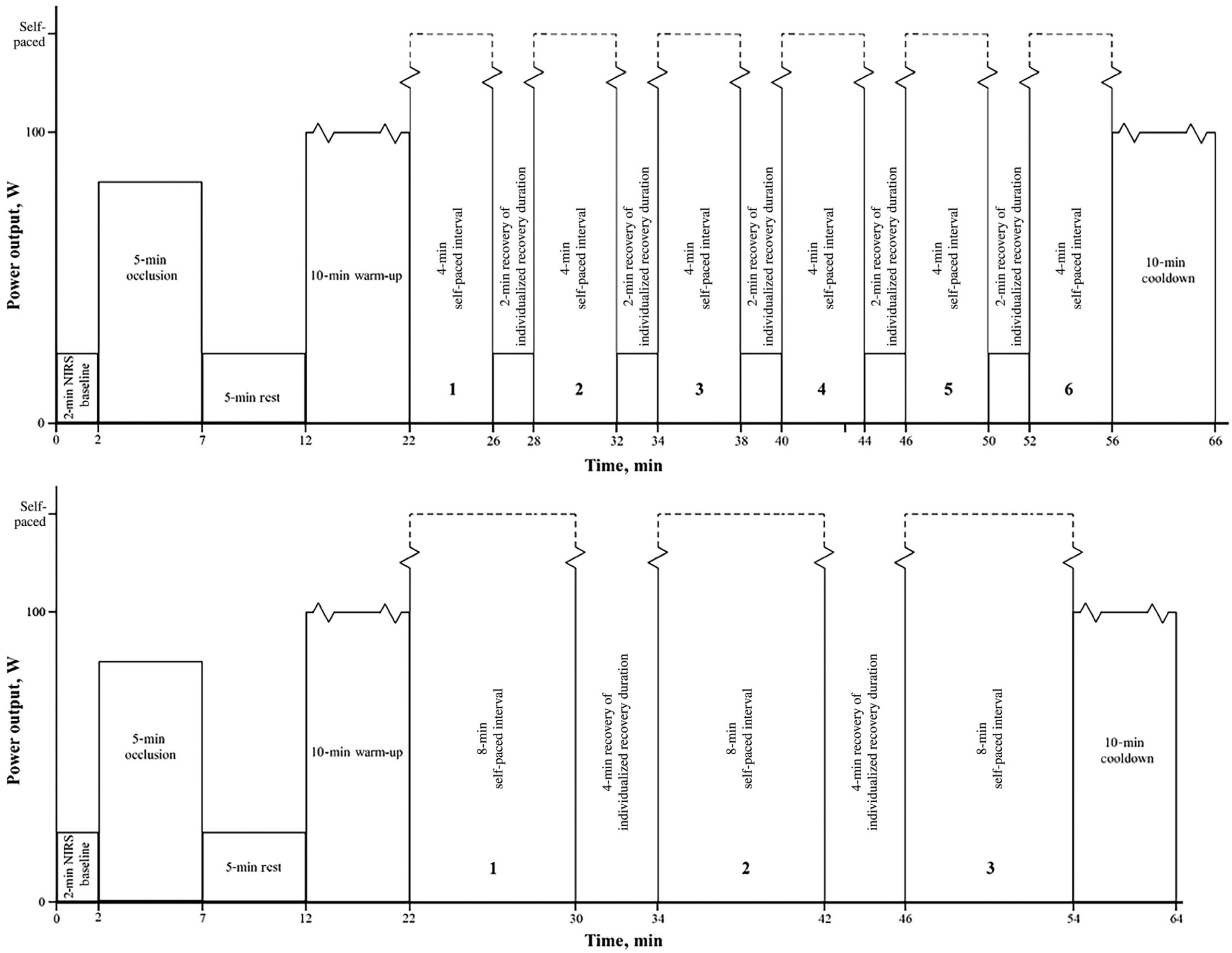


**Figure 3** — Schematic for the 6 × 4-minute HIIT protocol (top), schematic for the 3 × 8-minute HIIT protocol (bottom). HIIT indicates high-intensity interval training; NIRS, near-infrared spectroscopy.

respectively, (2:1 work:recovery ratio). The participants' IND recovery durations were 205 (79) and 200 (81) seconds for the 6 × 4- and 3 × 8-minute HIIT sessions, respectively, as measured in Visit 2.

Work intervals were prescribed as self-paced on a "maximal session effort" basis with participants instructed to achieve the highest PO possible during each interval. The HIIT sessions commenced with a 10-minute warm-up at 100 W and finished with a 10-minute cooldown at 100 W. All recovery intervals were passive, with participants instructed to remain seated with their right leg at the bottom of the pedal stroke.

The PO, HR, and respiratory gases were measured continuously throughout the HIIT sessions. The NIRS derived HHb was measured at the vastus lateralis muscle using a continuous-wave NIRS device during the recovery intervals of all HIIT sessions. The HHb data are reported as percentages of a 5-minute ischemic calibration performed prior to each HIIT session.[25] Blood lactate (B[La]) samples were taken pre-warm-up and during the last 30 seconds of each work interval via the fingertip (Biosen C-Line, EKF Diagnostic, London, United Kingdom). The RPE measurements were taken during the last 15 seconds of each work interval using the Borg 6 to 20 scale.[24] Session RPE (sRPE) measurements using a 0 to 10 scale were taken at the end of the 10-minute cooldown.

## Statistical Analyses

Data were presented as individual values or mean (SD) (unless specified otherwise). Statistical analyses were conducted using IBM SPSS Statistics (version 26; IBM, Armonk, NY). Visual inspection of Q–Q plots and Shapiro–Wilk statistics were used to check whether data were normally distributed. Three separate 2-way repeated-measures analysis of variance, 2 HIIT protocols (6 × 4- vs 3 × 8-min) × 2 recovery durations (STD vs IND), 2 recovery durations (STD vs IND) × number of work intervals, and 2 recovery durations (STD vs IND) × number of recovery intervals were used to determine between- and within-condition effects for all dependent variables. Bonferroni post hoc comparisons were used when a main effect or interaction was significant. Partial eta squared ($\eta_p^2$) were computed as effect size estimates and were defined as small ($\eta_p^2$ = .01), medium ($\eta_p^2$ = .06), and large ($\eta_p^2$ = .14).[27] The significance level was set at $P < .05$ in all cases.

## Results

Participants' characteristics are presented in Table 1.

Recovery duration had no effect on the time spent at >80% MMP ($P = .14$; $\eta_p^2 = .14$), >90% MMP ($P = .17$; $\eta_p^2 = .12$), and >95% MMP ($P = .48$; $\eta_p^2 = .03$) during the work intervals of the 6 × 4- and 3 × 8-minute HIIT sessions. Recovery duration had no effect on the time spent at >90%$\dot{V}O_2$max ($P = .18$; $\eta_p^2 = .12$) and >95%$\dot{V}O_2$max ($P = .26$; $\eta_p^2 = .08$) during the work intervals of the 6 × 4- and 3 × 8-minute HIIT sessions. Recovery duration had no effect on the time spent >90% $HR_{max}$ ($P = .17$; $\eta_p^2 = .15$) and >95% $HR_{max}$ ($P = .17$; $\eta_p^2 = .15$) during the work intervals of the 6 × 4- and 3 × 8-minute HIIT sessions (Table 2).

Statistics and effect size estimations from the second analysis of variance for each work interval variable are shown in Table 3. There were interactions found between recovery duration and work interval for PO (6 × 4) and B[La] (6 × 4). No interactions between recovery duration and work intervals were found for PO (3 × 8), HR, $\dot{V}O_2$, B[La] (3 × 8), and RPE. There were no main effects of recovery duration for HR, $\dot{V}O_2$, B[La], and RPE. There was a main effect of work interval number found for PO (6 × 4), HR, $\dot{V}O_2$, B[La], and RPE, but not for PO (3 × 8). The main effect of session type was found for PO and HR.

There was no effect of recovery duration on perceptual responses with similar sRPE values reported for the 6 × 4-minute (STD, 8.4 [0.6] vs IND, 8.3 [0.8]) and the 3 × 8-minute HIIT session (STD, 8.5 [0.7] vs IND, 8.3 [0.6]; $P = .26$; $\eta_p^2 = .08$).

Mean recovery interval HR (144 [5] vs 134 [6] bpm; $P = .005$; $\eta_p^2 = .47$) and $\dot{V}O_2$ (1.88 [0.29] vs 1.52 [0.32] L·min$^{-1}$; $P = .002$; $\eta_p^2 = .49$) were significantly lower during the IND 6 × 4-minute compared with the STD 6 × 4-minute HIIT sessions. There was no significant difference in mean recovery interval HR (130 [4] vs 133 [3] bpm; $P = .29$; $\eta_p^2 = .08$) and $\dot{V}O_2$ (1.36 [0.21] vs 1.46 [0.22] L·min$^{-1}$; $P = .17$; $\eta_p^2 = .12$) during the STD and IND 3 × 8-minute HIIT sessions.

Recovery duration had no effect on %HHb at the end of the recovery intervals (last 30-s average) for the 6 × 4-minute (STD, 11.7% [3.2%] vs IND, 17.3% [5.2%]) and 3 × 8-minute HIIT sessions (STD, 15.8% [3.8%] vs IND, 15.1% [4.9%]; $P = .07$; $\eta_p^2 = .22$).

**Table 1 Participant Characteristics and Preliminary Test Results**

| Variable | Values |
|---|---|
| Age, y | 32 (13) |
| Height, cm | 177.9 (5.2) |
| Mass, kg | 72.4 (9.1) |
| 4-min IND m$\dot{V}O_2$ duration, s | 205 (79) |
| 8-min IND m$\dot{V}O_2$ duration, s | 200 (81) |
| VL skin fold, mm | 8.8 (2.1) |
| Thigh circumference, cm | 53.0 (6.6) |
| $\dot{V}O_2$max, L·min$^{-1}$ | 4.3 (0.6) |
| Relative $\dot{V}O_2$max, mL·kg·min$^{-1}$ | 60 (7) |
| MMP, W | 373 (57) |
| Relative MMP, W·kg$^{-1}$ | 5.2 (0.7) |
| $HR_{max}$, bpm | 188 (12) |
| Years training | 5.6 (4.4) |
| Years competing | 5.3 (3.5) |
| Mean weekly training hours | 10.1 (4.4) |

Abbreviations: IND, m$\dot{V}O_2$ recovery duration to baseline; $HR_{max}$, maximal minute heart rate; MMP, maximal minute power; m$\dot{V}O_2$, muscle oxygen consumption; VL, vastus lateralis muscle; $\dot{V}O_2$max, maximal oxygen consumption. Note: Data are represented as mean (SD).

## Discussion

The main finding of this study was that the IND recovery duration did not improve the performance or acute physiological response of the work intervals when compared with the STD recovery duration in well-trained cyclists. Specifically, mean POs were not significantly different between the IND and STD recovery conditions for both the 6 × 4- and 3 × 8-minute HIIT sessions (Figure 4A and 4B). As recovery duration had no effect on the mean work interval intensity (Figure 4A and 4B), it is not surprising that there was no significant effect on the physiological and metabolic response during the work intervals for both the 6 × 4- and 3 × 8-minute HIIT sessions (Figure 4 and Table 3).

Based on the m$\dot{V}O_2$ recovery response of the current study, it can be assumed the 120-second STD recovery duration would have not provided the same recovery at the exercising muscle, in comparison with the longer IND recovery durations (205 [79] s) intended to provide a more complete metabolic recovery during the 6 × 4-minute HIIT session. However, despite the shorter recovery provided during the STD 6 × 4-minute HIIT session, the performance of the work intervals was not affected. Within the session, NIRS data demonstrates a similar %HHb at the end of the 120-second recovery intervals when compared with all other recovery interval durations. These data demonstrate that 120-second recovery may be long enough for adequate $O_2$ delivery to the exercising muscle, allowing key recovery process to occur to such an extent that work interval performances could be maintained (ie, resynthesis of adenosine triphosphate, PCr, restoration of

**Table 2 Time in Seconds Spent Above Percentages of $\dot{V}O_2$max, $HR_{max}$, and MMP During Work Intervals**

| | Time at %$\dot{V}O_2$max | | | Time at %$HR_{max}$ | | | Time at %MMP | | |
|---|---|---|---|---|---|---|---|---|---|
| Prescription | 80 | 90 | 95 | 80 | 90 | 95 | 80 | 90 | 95 |
| STD 6 × 4 | 1178 (139) | 821 (311) | 502 (332) | 1248 (67) | 869 (280) | 470 (271) | 790 (380) | 96 (75) | 48 (45) |
| IND 6 × 4 | 1156 (153) | 749 (364) | 451 (390) | 1244 (82) | 841 (282) | 402 (282) | 880 (458) | 125 (106) | 40 (37) |
| STD 3 × 8 | 1202 (126) | 753 (396) | 398 (330) | 1301 (67) | 943 (325) | 550 (301) | 489 (317) | 46 (34) | 24 (26) |
| IND 3 × 8 | 1176 (176) | 649 (345) | 278 (258) | 1295 (66) | 875 (333) | 437 (286) | 563 (313) | 50 (22) | 23 (18) |

Abbreviations: $HR_{max}$, maximal minute heart rate; IND, individualized; MMP, maximal minute power; STD, standardized; $\dot{V}O_2$, maximal oxygen consumption.

**Table 3 Statistics and Effect Size Estimations From Analysis of Variance for Each Work Interval Variable Analyzed**

| | | Interaction (duration × interval) | | | Main effect of recovery duration | | | Main effect of work interval number | | | Main effect of session type (6 × 4 vs 3 × 8) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | Prescription | *F* | *P* | $\eta_p^2$ | *F* | *P* | $\eta_p^2$ | *F* | *P* | $\eta_p^2$ | *F* | *P* | $\eta_p^2$ |
| PO | 6 × 4 | 3.21 | .01* | .18 | 1.95 | .18 | .12 | 7.33 | <.001* | .33 | 58.29 | <.001* | .80 |
| | 3 × 8 | 1.95 | .16 | .12 | 3.73 | .07 | .20 | 2.54 | .10 | .15 | | | |
| HR | 6 × 4 | 0.77 | .57 | .06 | 0.02 | .88 | .002 | 43.29 | <.001* | .77 | 11.98 | .005* | .50 |
| | 3 × 8 | 3.25 | .05 | .19 | 4.52 | .05 | .24 | 40.04 | <.001* | .74 | | | |
| $\dot{V}O_2$ | 6 × 4 | 2.05 | .08 | .12 | 1.16 | .30 | .07 | 12.94 | <.001* | .46 | 0.06 | .81 | .004 |
| | 3 × 8 | 0.06 | .94 | .004 | 0.75 | .40 | .05 | 17.42 | <.001* | .54 | | | |
| B[La] | 6 × 4 | 4.41 | .001* | .23 | 0.90 | .36 | .06 | 22.91 | <.001* | .60 | 0.06 | .81 | .005 |
| | 3 × 8 | 1.45 | .25 | .10 | 0.13 | .73 | .01 | 13.14 | <.001* | .50 | | | |
| RPE | 6 × 4 | 0.58 | .72 | .04 | 0.23 | .64 | .02 | 55.22 | <.001* | .79 | 2.46 | .14 | .14 |
| | 3 × 8 | 1.26 | .30 | .08 | 1.61 | .22 | .10 | 50.85 | <.001* | .77 | | | |

Abbreviations: B[La], blood lactate; HR, heart rate; PO, power output; RPE, rating of perceived exertion; $VO_2$, oxygen consumption.
*Statistical significance.

myoglobin $O_2$ stores, and muscle lactate utilization). This may provide further insight for previous research, which similarly found increases in recovery interval duration beyond 120 seconds during 6 × 4-minute HIIT sessions do not induce any additional benefits for subsequent work bouts.[3–5] In the case of the 3 × 8-minute HIIT sessions, the STD recovery duration (240 s) was longer than the IND recovery duration (200 [81] s). Therefore, it would be assumed that a similar metabolic recovery was attained during both recovery prescriptions, hence the similar work interval performances. This suggests that a full recovery of m$\dot{V}O_2$ may not be required to maximize work interval performance during HIIT.

In agreement with Schoenmakers and Reed[4] and Smilios et al,[3] the current study found recovery interval duration to have no effect on the time participants spent exercising >90 and >95% of $\dot{V}O_2$max and $HR_{max}$ during the work intervals (Table 2), despite subsequent work intervals starting from a lower $\dot{V}O_2$ after the longer recovery intervals. Schoenmakers and Reed[4] reported that shorter recovery intervals (1 min) resulted in an increased metabolic rate at the start of the next work interval, which lengthened the time needed to reach a $\dot{V}O_2$ plateau. Furthermore, the mean response time of $\dot{V}O_2$ and HR was found to be faster after longer recovery intervals (≥ 3 min) and was accompanied by higher $\dot{V}O_2$ and HR amplitude.[3,4] This explains why similar times spent at >90 and >95% of $\dot{V}O_2$max and $HR_{max}$ were found between recovery durations, despite the work intervals starting from a lower $\dot{V}O_2$ and HR after the longer recovery intervals. The HR and $\dot{V}O_2$ results of the current study do not support the implementation of the IND recovery duration, over the STD 2:1 work recovery ratio. Nevertheless, the current study results and those of Schoenmakers and Reed[4] and Smilios et al[3] show that shorter recovery intervals (≤ 2 min) allow for a higher percentage of the overall session to be completed at >90% $\dot{V}O_2$max resulting in greater accumulation of physiological stress relative to the total time spent training, making for a more time-efficient HIIT session.

Recovery interval duration had no effect on reported RPE or sRPE values, during both the 6 × 4- and 3 × 8-minute HIIT sessions (Figure 4I and 4J). Throughout all 4 HIIT sessions, there was a linear increase in work interval RPE with reported values reaching between 18 and 19 at the last work interval. This linear increase in RPE occurred despite the mean PO being relatively consistent across the work intervals (Figure 4A and 4B). Similar increases in RPE have been observed in previous HIIT studies involving well-trained runners, despite the participants maintaining a relatively constant running velocity across the work intervals.[4,5,13] The upward drift in RPE can be attributed to the increasing physiological, biomechanical, and psychological stress the participants experienced as the HIIT sessions progressed.[28,29]

To establish recovery duration, the current study measured m$\dot{V}O_2$ response after a single 4- or 8-minute high-intensity work interval and then applied this to a HIIT session of multiple high-intensity work intervals. It is important to note that restoration of PCr, which is closely linked to the time constant for m$\dot{V}O_2$ recovery, takes longer as HIIT sessions progress,[30] and so it is likely that the optimal recovery duration required between work intervals changes across a HIIT session. Therefore, the measurement of m$\dot{V}O_2$ response, and thus recovery duration, after a single high-intensity work interval may not be reflective of that performed following a series of HIIT intervals.

## Practical Applications

By increasing or decreasing the recovery interval duration within the range of the 2:1 work recovery ratio, this study has found there to be no significant effect on the performance of subsequent work intervals and the acute physiological and perceptual response to the HIIT session (when using passive recoveries). Coaches and athletes should consider utilizing the 2:1 work recovery ratio when programming long work interval (4- or 8-min) HIIT sessions. In doing so, they can be reasonably confident they are achieving adequate recovery between work intervals while maximizing the time spent training. Importantly, this study used a cohort of trained cyclists, and so caution is advised when extrapolating findings beyond the scope of the current study.

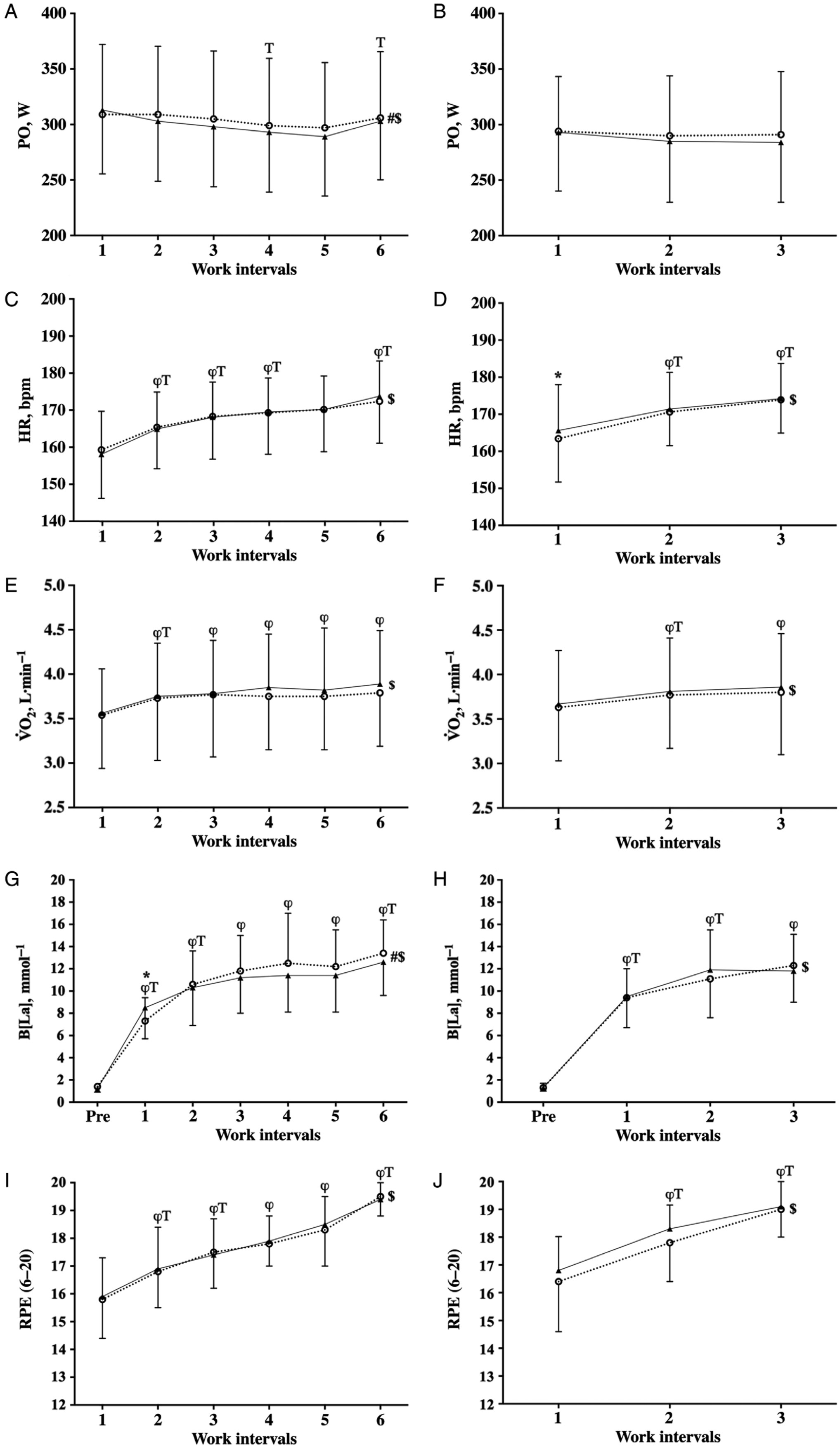


**Figure 4** — (A/B) Mean PO, (C/D) mean HR, (E/F) mean $\dot{V}O_2$, (G/H) mean B[La], (I/J) mean RPE. Data are displayed per work interval as mean (SD) for the 6 × 4- and 3 × 8-minute HIIT sessions with STD recovery duration (closed triangles) and IND recovery duration (open circles). $^{\phi}$Significant difference from interval 1 (all $P < .05$). $^{T}$Significant difference from previous interval (all $P < .05$). $^{\$}$Main effect of work interval number (all $P < .001$). $^{\#}$Interaction between recovery duration and work interval (all $P < .05$). *Significant difference between recovery durations (all $P < .05$). B[La] indicates blood lactate; HR, heart rate; PO, power output; RPE, rating of perceived exertion; $\dot{V}O_2$, oxygen consumption.

## Conclusion

Individualizing HIIT recovery duration based upon the resolution of m$\dot{V}O_2$ to baseline levels does not improve the performance of the work intervals or the acute physiological response of the HIIT session when compared with an STD 2:1 recovery duration.

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