ACUTE CARDIOPULMONARY, METABOLIC, AND NEUROMUSCULAR RESPONSES TO SEVERE-INTENSITY INTERMITTENT EXERCISES

Running Head

Acute responses to severe-intensity intermittent exercises

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ABSTRACT

The purpose of this study was to compare cardiopulmonary, neuromuscular, and metabolic responses to severe-intensity intermittent exercises with variable or constant work rate. Eleven cyclists (28 ± 5 years; 74 ± 7 kg; 175 ± 5 cm; 63 ± 4 mL·kg⁻¹·min⁻¹) performed the following tests until exhaustion on separate days: 1) an incremental test; 2) in random order, two constant work rate tests at 95% and 110% of the peak power for the determination of Critical Power (CP); 3) 2–4 tests for the determination of the highest power that still permits the achievement of maximal oxygen uptake ($P_{\text{HIGH}}$); and 4) two random severe-intensity intermittent exercises. The last two sessions consisted of a constant work rate (CWR) exercise performed at $P_{\text{HIGH}}$ or a decreasing work rate (DWR) exercise from $P_{\text{HIGH}}$ until 105% of CP. Compared to CWR, DWR presented higher time to exhaustion (635 ± 223 vs. 274 ± 65 s), time spent above 95% of VO$_2$max ($t_{95\%\text{VO}_2\text{max}}$) (323 ± 227 vs. 98 ± 65 s), and O$_2$ consumed (0.97 ± 0.41 vs. 0.41 ± 0.11 L). Electromyography amplitude (RMS) decreased for DWR but increased for CWR during each repetition. However, RMS and VO$_2$ divided by power output (RMS/PO and VO$_2$/PO ratio) increased in every repetition for both protocols, but to a higher extent and slope for DWR. These
findings suggest that the higher RMS/PO and VO$_2$/PO ratio in association with the longer exercise duration seemed to have been responsible for the higher t95%VO$_{2\text{max}}$ observed during severe DWR exercise.

**Key-words:** cycling; critical power; electromyography; severe domain; VO$_{2\text{max}}$; VO$_2$ slow component.

**ABBREVIATIONS LIST**

VO$_{2\text{max}}$: Maximal oxygen uptake  
t95%VO$_{2\text{max}}$: Time spent at VO$_{2\text{max}}$  
DWR: Decreasing work rate  
EMG: Integrated electromyography  
CP: Critical power  
P$_{\text{HIGH}}$: The highest constant intensity at which VO$_{2\text{max}}$ is attained  
CWR: Constant work rate  
P$_{\text{PEAK}}$: Peak power associated with the end of the incremental test  
T$_{\text{LOW}}$: The lowest exercise duration at which VO$_{2\text{max}}$ is attained  
VO$_2$: Pulmonary oxygen uptake  
VO$_2$/PO ratio: The ratio between VO$_2$ and absolute power output  
RMS: Root mean square  
RMS/PO ratio: The ratio between RMS and absolute power output
Maximal oxygen uptake (VO$_{2}$max) is defined as the highest rate at which oxygen can be taken up and utilized by the body during severe exercise (3). VO$_{2}$max is one of the most relevant parameters for determining the effectiveness of the cardiorespiratory system, and moreover, it is an important physiological determinant of cycling performance (18). Given these applications of VO$_{2}$max, there has been considerable interest among coaches and endurance cyclists to enhance VO$_{2}$max to its maximum trainable upper limit (23). Although the optimal training stimuli have not been clearly defined for producing the greatest improvement in VO$_{2}$max, recent study has suggested that high-intensity interval training might induce greater increases in VO$_{2}$max than continuous exercise due to a greater amount of time spent at a high percentage of VO$_{2}$max (27).

Many attempts combining different volumes, intensities, and work-interval durations have been made in order to optimize the time spent at or near VO$_{2}$max during intermittent exercise (5, 6, 24). However, the effectiveness of variable work rate exercise, particularly during a decreasing work rate (DWR) protocol, in prolonging the time at VO$_{2}$max remains unclear. The maintenance of VO$_{2}$max during shorter (32) and longer (4, 19) DWR exercises, despite the work rate falling considerably below that associated with the attainment of VO$_{2}$max during incremental exercise, has been reported previously. In addition, Vanhatalo et al. (32) reported that a higher amount of time at VO$_{2}$max during DWR exercise was accompanied by a significantly greater pulmonary oxygen consumption (VO$_{2}$) and integrated electromyography (EMG) relative to work rate compared to constant work-matched exercise of the same duration. This later result suggests that the mechanism behind the maintenance of VO$_{2}$max with DWR for continuous severe
exercise could be the same that was proposed to explain the development of the VO$_2$
slow component-like phenomenon (9, 14). At work rates above the so-called critical
power (CP) (i.e., severe-intensity exercise domain), neuromuscular activity increases
over time and VO$_2$ slow component can cause VO$_2$ to attain its maximum, with
exhaustion occurring soon afterwards (25). Additionally, fast-start pace strategy (a
kind of DWR exercise), which would be expected to spare anaerobic reserve
utilisation, seems to increase total work done during severe-intensity exercises (2,
17, 30). Thus, intermittent exercise adopting a DWR approach by using the entire
range of the severe-intensity domain (from supramaximal to submaximal) during
each exercise bout could be useful for prolonging exercise tolerance and the time
near VO$_2$max.

Based on the above scenario, severe-intensity intermittent exercise sessions
were designed to primarily elicit peak cardiopulmonary strain in parallel with highest
possible neuromuscular and metabolic stimulus. We, therefore, determined the
highest and the lowest (105% of CP) intensities that allowed the achievement of
VO$_2$max, designed as the upper and lower boundaries of the severe exercise domain,
respectively (10, 15) to individualize the exercise sessions. Theoretically, a DWR
exercise bout performed throughout the severe-intensity domain could: 1) provide a
continuous stimulus to drive and to keep VO$_2$ at its maximum values; 2) permit
higher work length intervals (i.e., exercise tolerance) by decreasing the work rate to
submaximal intensity; and hence, 3) increase exercise duration near VO$_2$max
compared to constant work rate (CWR) exercise.
Thus, this study aimed to: 1) investigate cardiopulmonary, neuromuscular, and metabolic responses to severe-intensity intermittent exercises; and 2) identify key features of variable vs. constant work rate protocols that would provide a high cardiopulmonary and neuromuscular strain, and thus, be expected to provide a strong adaptive stimulus during exercise training. The main hypothesis was that longer exercise duration near VO$_2$max would be observed during DWR compared with CWR intermittent exercise due to the greater magnitudes of oxygen and neuromuscular cost reported during DWR exercise (32). Knowledge about the acute framework of severe exercise protocols could contribute to the understanding of the determinants of severe-intensity intermittent exercises, providing helpful information for training science and practice, as many athletes incorporate severe high-intensity interval training sessions within their training programs.

**METHODS**

**Experimental Approach to the Problem**

To understand the acute responses to severe-intensity intermittent exercises, the subjects visited the laboratory for four phases of experimentation with at least 48 h separating each visit. The four phases of the study comprised: 1) an incremental test in order to determine VO$_2$max and peak power associated with the end of the test (P$_{PEAK}$); 2) two laboratory test sessions until exhaustion in a random order at 95% and 110% of P$_{PEAK}$ to determine additional values of VO$_2$max and CP model parameters; 3) two to four CWR tests to determine the highest constant intensity at which VO$_2$max is attained (P$_{HIGH}$) and the lowest exercise duration at which VO$_2$max is attained (T$_{LOW}$); and 4) two randomised intermittent exercise sessions until exhaustion with different work rate manipulations (i.e., CWR or DWR profile)
All tests were performed at the same time of day (± 2 h) and completed within 3 weeks. All tests were performed using an electromagnetic cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands). During each test, subjects were blinded to the time elapsed during exercise and encouraged to continue for as long as possible until volitional exhaustion. The independent variable was exercise protocol, whereas the dependent variable included the cardiopulmonary, metabolic, and neuromuscular variables.

**Figure 1 about here**

**Subjects**

Eleven trained cyclists (age, 28 ± 5 years; weight, 74 ± 7 kg; height, 175 ± 5 cm; VO2max, 63 ± 4 mL·kg⁻¹·min⁻¹) volunteered for this cross-over study. All subjects were apparently healthy non-smokers, with no injury and medication use, who practiced cycling for at least 2 years before the study. Before the test protocol, they were all informed about the testing procedures and provided written informed consent. All subjects were naive to the purpose of the study. The subjects were instructed to avoid strenuous exercise for 24 h before a test session and to arrive at the laboratory in a rested and fully hydrated state. Besides that, the subjects were instructed to maintain a regular diet during all protocol and to have their last light meal 2 hours before each test. The study was performed according to the Declaration of Helsinki, and the protocol was approved by the Institutional Research Ethics Committee.
Procedures

For phases 2 and 3, the tests were preceded by a warm-up consisting of 5 min of continuous cycling at 50% of $P_{\text{PEAK}}$ followed by a 5-min rest period. In phase 4, the warm-up consisted of 10 min of continuous cycling at 50% of $P_{\text{PEAK}}$ followed by a 5-min rest period. All tests were performed until exhaustion and were terminated when the subject could not maintain a cadence of above 60 rpm.

Throughout each test, $V_{\text{O}_2}$, respiratory frequency and minute ventilation were measured breath-by-breath using an automated open-circuit gas analysis system (Quark CPET, Cosmed Srl, Rome, Italy). Before each test, gas analysers were calibrated using ambient air and gases containing 16% oxygen and 5% carbon dioxide. The turbine flow meter used for the determination of minute ventilation was calibrated with a 3-L calibration syringe (Cosmed Srl, Rome, Italy). Heart rate was continuously measured with a telemetric heart rate monitor (Cosmed Srl, Rome, Italy).

Incremental test (Phase 1). The initial power was set at 110 W and increased by 35 W every 3 min until exhaustion. $V_{\text{O}_2}$ was reduced to 15-s average values and the highest 15-s $V_{\text{O}_2}$ value reached was considered to as the subject’s $V_{\text{O}_2}\max$. The $P_{\text{PEAK}}$ was defined as the final intensity achieved at the end of the test.

Determination of Critical power and Time to exhaustion (Phase 2). Each subject performed two constant tests at 95% and 110% of $P_{\text{PEAK}}$ on separate days in a random order. $P_{\text{HIGH}}$ trial was also included in the model in order to increase confidence in the accuracy of CP determination. Time to exhaustion was recorded to the nearest second and the CP was calculated according to the linear regression model of work rate vs. time$^{-1}$ (33). The total amount of work that can be performed above CP was determined by the same work rate vs. time$^{-1}$ model.
Determination of $P_{HIGH}$ and $T_{LOW}$ (Phase 3). The subjects performed 2 to 4 CWR exercises until exhaustion to directly determine $P_{HIGH}$. The work rate of the first test corresponded to 130% $P_{PEAK}$. If during the first CWR test, VO$_2$max could be attained or maintained, subsequent CWR tests at a 5% higher work rate were performed on separate days until VO$_2$max could not be reached. If during the first CWR test, VO$_2$max could not be reached or maintained, further CWR tests were conducted with subsequently reduced work rate (5%). $P_{HIGH}$ was defined for each subject as the highest power output at which the highest 15-s VO$_2$ average, determined from rolling averages of 5-s samples, was equal to or higher than VO$_2$max (averaging the highest VO$_2$ values from incremental and CWR tests) minus one typical error of measurement (10). $T_{LOW}$ was the time to exhaustion performed at $P_{HIGH}$.

Severe-intensity intermittent exercises (Phase 4). Finally, subjects performed two protocols of severe-intensity intermittent exercises until exhaustion in a random order using $P_{HIGH}$ and $T_{LOW}$ as parameters to formulate an individualized exercise session (Figure 1). In the CWR test, $P_{HIGH}$ was fixed as workload, and repetition time comprised 60% of $T_{LOW}$. In the DWR test, $T_{LOW}$ was fixed as repetition time and divided into four equal steps within each repetition. The first work rate corresponded to $P_{HIGH}$ and the last step corresponded to 105% of CP. The two intermediated work rates were chosen to match the work above CP with CWR. In both protocols, a work-to-rest ratio of 1:1 was adopted, and exercise recovery was performed at 30% of $P_{PEAK}$. The peak minute ventilation, peak respiratory frequency and peak heart rate were identified as the higher value of a 10-second average. The total amount of O$_2$ consumed was calculated by integrating the area under 5-s VO$_2$ values measured during exercise and expressed relative to body mass (mL·kg$^{-1}$). The time spent at or above 95% of VO$_2$max ($t_{95\%VO_2max}$) was determined from VO$_2$ values higher
than or equal to 95%VO\textsubscript{2}max; t95%VO\textsubscript{2}max was also expressed as a function of the exercise time. The VO\textsubscript{2} normalized by power output (VO\textsubscript{2}/PO ratio) was also computed during the test. Immediately after the last repetition in both severe-intensity intermittent exercises, a blood sample was taken from the earlobe to measure end blood lactate concentration (YSI 1500 Sport, Yellow Springs Instruments, OH, USA). At the same time, blood samples were taken from a finger in a heparinized capillary tube (150 µL) to analyse end blood pH. Within 5 min of collection, all blood samples were analysed at 37°C (GEM Premier 3000, Instrumentation Laboratory, Lexington, USA).

**EMG signal analysis and processing.** Surface EMG was used to measure muscle activity of the *vastus lateralis*. EMG signals were collected using a Miograph system (MioTec Biomedical, Porto Alegre, RS, Brazil) with a common rejection mode of 110 dB, impedance input of 1TX, and resolution of 14-bits at a sampling rate of 2000 Hz. Bipolar single differential surface EMG sensors (Ag/AgCl) with a diameter of 22 mm and centre-to-centre distance between electrodes of 25 mm (Kendall Meditrace, Chicopee, Canada) were positioned on the skin of right thigh after careful shaving and cleaning of the area, using an abrasive cleaner and alcohol swabs to reduce skin impedance. The electrodes were placed longitudinally over the muscle belly in the approximate fibre direction in accordance with the International Society of Electromyography and Kinesiology (22). The reference electrode was positioned over the styloid process of the ulna. To minimize movement artefacts, an elastic bandage was wrapped around electrode wires. Permanent pen marks were made around the electrodes to enable reproduction of the placement on subsequent tests.
The raw EMG signals were smoothed using a recursive fifth-order band-pass Butterworth digital filter with a frequency range set between 10 and 500 Hz. Off-line analyses of EMG signals were developed with custom-written scripts (MATLAB 7.0, Mathworks Inc., Novi, MI, USA). The EMG signals were obtained throughout exercise protocol. For further analyses, root mean squared (RMS) values only for the first, the second, and the last repetitions for both exercise protocols. In these repetitions, RMS value was calculated using two time windows (i.e., Start and Final portion) relative to the repetition duration, one from the start (10 to 20-s) and the other from the final (77.5 to 97.5 % of repetition time). The bound’s values of the onset of each repetition (i.e., 10-s) and 2.5 % for the end of each repetition were neglected avoiding a cycle ergometer workload adjustment and to accommodate the preferred cadence of the athlete. Thus, the means of the remainder values were used for representing each time window. As a threshold criterion for the determination of the muscle activation–deactivation dynamics, only values above 10% of the peak value of the first window were considered valid. EMG signals were normalized by the average value at the beginning of the protocol (first window at the first repetition: 10 to 20-s). The RMS/PO ratio was computed dividing the normalized RMS value by the absolute power output. Additionally, the RMS/PO ratio increase (or lack thereof) during each repetition of DWR and CWR was determined from the angular coefficient (i.e., slope) by the linear relationship between RMS/PO ratio and percentage of time elapsed.

**Statistical analysis.** Standard methods of descriptive analysis were used for the calculations of mean and standard deviation (SD). A paired Student’s t-test was used to compare differences in performance and physiological values between the two protocols, i.e., DWR and CWR. A two-way repeated measures ANOVA (2 × 3;
protocol by repetition) was used to analyse the EMG parameters (RMS and RMS/PO ratio) as a function of repetition (first, second, and last). When the sphericity assumption was violated, the Greenhouse-Geisser adjustment was performed. When significant differences were found, the Bonferroni test was employed to determine their origin. Pearson’s correlation coefficient was used to compare VO$_2$ and RMS/PO ratio during repetitions in each protocol. For all statistical analyses, the level of statistical significance was set at $p \leq 0.05$.

RESULTS

Incremental and CWR tests. The responses from the incremental and constant work rate tests to exhaustion are presented in Table 1. The VO$_2$max (determined by averaging the highest VO$_2$ values from incremental and constant work rate tests minus one typical error of measurement) was $4716 \pm 496$ mL·min$^{-1}$, and it was associated with a typical error of measurement between 1.2% and 5.8% (3.2 ± 1.3%). The amplitude of the severe intensity domain corresponded to 148 ± 29 W, or expressed as relative intensity, from 84 ± 5% to 129 ± 10% of P$_{PEAK}$. The mean duration of bout and rest interval (work-to-rest ratio 1:1) was 124 ± 27 s for DWR and 74 ± 16 s for CWR.

Table 1 about here

Physiological and performance parameters during severe-intensity intermittent exercises. Physiological and performance parameters obtained during DWR and CWR exercise sessions are presented in Table 2. The DWR protocol presented a greater number of repetitions ($p < 0.01$), time to exhaustion ($p < 0.01$), total work done ($p < 0.01$), total t95%VO$_2$max in absolute ($p < 0.01$), and relative to time to exhaustion values ($p = 0.03$), and total amount of O$_2$ consumed ($p < 0.01$) compared
to CWR. At the end of the exercise, peak minute ventilation and pH were lower in DWR (p < 0.01 and p = 0.03, respectively) with no substantial differences in peak respiratory frequency, peak heart rate and blood lactate concentration between sessions (p > 0.05).

Table 2 about here

Muscle activity during severe-intensity intermittent exercises. Muscle activity parameters (RMS value and RMS/PO ratio) at Start and Final portion of the exercise time for the first, second, and last repetition during DWR and CWR are presented in Figure 2. While RMS values increased between Start to Final portion of all analysed repetitions in CWR, RMS values significantly decreased between Start and Final portion in all analyzed repetitions during DWR. However, RMS/PO ratio increased between Start to Final portion of all analysed repetitions in both CWR and DWR. Furthermore, when the slope of RMS/PO ratio vs. the percentage of repetition time elapsed was analysed, it was higher in DWR than in compared to CWR in the first (0.001 ± 0.0006 vs. 0.0003 ± 0.0002 RMS·% of time⁻¹; p < 0.01), the second (0.001 ± 0.0007 vs. 0.0004 ± 0.0004 RMS·% of time⁻¹; p < 0.01), and the last repetition (0.001 ± 0.0007 vs. 0.0005 ± 0.0005 RMS·% of time⁻¹; p = 0.02).

Figure 2 about here

RMS values and RMS/PO ratio at Final portion in each repetition showed a progressive increase from the first to the second repetition and from the first to the last repetition, with no differences from the second to the last repetition in CWR. With regard to Start portion, a difference was observed only for first to last repetition in CWR (p < 0.01). RMS values and RMS/PO ratio did not presented significant difference in DWR. The average values of VO₂/PO ratio and RMS/PO ratio calculated from Final portion of each repetition analysed were largely correlated in
both DWR \( r = 0.68 (0.47 – 0.82); p < 0.05 \) and CWR \( r = 0.88 (0.78 – 0.94); p < 0.05 \) exercises. The temporal profiles of the \( \text{VO}_2 \) and RMS responses during both protocols are shown in Figure 3.

**Figure 3 about here**

**DISCUSSION**

In the present study, cardiopulmonary, metabolic, and neuromuscular responses as well exercise tolerance to two different severe-intensity intermittent exercise protocols were analysed in cyclists. Our main findings were as follows: 1) a considerable time was spent near \( \text{VO}_2 \text{max} \) during DWR exercise while the external work rate decreased to 105% of CP (~90%\( \text{VO}_2 \text{max} \)); 2) the magnitudes of \( t95\%\text{VO}_2 \text{max}, \text{VO}_2/\text{PO} \) ratio, and RMS/PO ratio measured during DWR exercise were significantly greater than those measured during CWR exercise (Figure 3); and 3) \( \text{VO}_2/\text{PO} \) ratio positively correlated with RMS/PO ratio for both DWR and CWR intermittent exercises. These findings support the notion that: 1) the increased oxygen cost is associated with the higher neuromuscular cost, irrespective of the protocol; and 2) a higher \( \text{VO}_2/\text{PO} \) and RMS/PO ratio in combination with longer exercise duration seems to be responsible for the longer \( t95\%\text{VO}_2 \text{max} \) observed during severe DWR exercise than during CWR exercise.

Our data reveal that DWR is accompanied by reduced RMS amplitude (taken as an estimate of fiber activation) during severe-intensity exercise. A concomitant decrease in the RMS value with a decrease in work rate was previously reported during all-out exercise (21, 32). Accordingly, the observed changes in the RMS value of the **vastus lateralis** muscle, associated with reductions in external mechanical output during DWR, permit the qualitative conclusion that changes in
locomotor muscle power output occurred in a similar direction to those of central
neural locomotor output for both unfatigued (first repetition) and fatigued (last
repetition) states. On the other hand, while RMS amplitude declined towards the
final portion of the repetition at DWR, RMS/PO ratio increased progressively
towards the final portion of the repetition for both exercise protocols, but at a higher
magnitude for DWR exercises. Furthermore, the slope of RMS/PO ratio was higher
in DWR than in CWR, strengthening a larger cost of motor unit activation per unit of
external work rate for DWR. These results seem to indicate a cumulative effect of
previous work rates, i.e., the reduction in the RMS amplitude (~8%) did not
completely follow the reduction in external mechanical output (~31%). Additionally,
the time effect seen during CWR should not be ruled out for DWR. The unmatched
decrease between RMS amplitude and work rate observed during DWR may be
responsible for maintaining high aerobic demand throughout the repetition, allowing
the effects of the higher initial work-load to remain at the end of each repetition (12,
32). The available evidence demonstrates that, at exercise onset, the \( \text{O}_2 \) cost of the
initially recruited type II fibers may only become fully manifest during the later
stages of decreasing work rate exercise (34). Therefore, an elevated initial
neuromuscular load may have contributed to the additional \( \text{O}_2 \) uptake in the
following lower work rates, which could have increased \( \text{VO}_2/\text{PO} \) ratio toward the
limit of tolerance for DWR exercise.

The lower values of \( \text{VO}_2/\text{PO} \) ratio observed for CWR must be interpreted
with caution, as the \( \text{VO}_2 \) response can be constrained by \( \text{VO}_2\text{max} \) during exercise
performed within the severe domain (15). Indeed, the lower increase in oxygen cost
during CWR (i.e., \( \text{VO}_2/\text{PO} \) ratio plateau) was probably because \( \text{VO}_2 \) cannot continue
to increase progressively beyond \( \text{VO}_2\text{max} \) (Figure 3). Despite the fact that \( \text{VO}_2 \) was
also constrained by VO$_2$\text{max} during DWR, VO$_2$/PO ratio increased progressively with decreasing workload, representing VO$_2$ slow component-like phenomenon (35). On the other hand, RMS/PO ratio values were not likely to be constrained by maximal values in both exercise protocols, but they were even higher and increased in a similar way as VO$_2$/PO ratio only during DWR. Although the values of VO$_2$/PO ratio during CWR were possibly underestimated, simultaneous analysis of VO$_2$ and RMS/PO ratio (Figure 3) suggests that a higher cost of the task during stationary cycling did indeed occur during DWR. While CWR apparently presented a lower locomotor cost, the exercise tolerance was shorter in this condition. It has been suggested that fatigue during high-intensity exercise is mediated by intramuscular factors probably related to metabolites accumulation (e.g., Pi and H$^+$) (16) than by neural adjustments (20). As our intermittent exercises were matched to spend similar amounts of work above CP by repetition, but DWR had a longer rest duration, the longer time to exhaustion observed during DWR support the notion that higher amounts of intramuscular metabolites were recovered by rest interval during DWR (11, 16, 31).

In the present study, the higher time to exhaustion during DWR probably contributed to the higher absolute t$_{95\%}$VO$_2$\text{max} (26), although t$_{95\%}$VO$_2$\text{max} remained higher during DWR as well when expressed relative to time to exhaustion. Additionally, the DWR protocol may lead to a slower rate of work above CP utilization, which would also contribute to prolonging time to exhaustion. Indeed, fast-start protocols have increased time to exhaustion in continuous (17, 30) and intermittent exercise (12), irrespective of exercise duration. On the other hand, one could speculate that the longer recovery duration between repetitions per se would be the primary cause of the higher time to exhaustion during DWR. This seems to be a
limitation for intermittent exercises using fixed work-to-rest ratio which by
manipulating different work durations led to differences in rest duration. Although
we are aware that different work-to-rest ratios (e.g., 1:2, 1:3) could be adopted to
prolong exercise duration, mainly in CWR, a longer recovery would reduce
$t95\%VO_{2\text{max}}$ (8), which was not the objective of the selected exercise protocols.
Therefore, we preferred to maintain the same work-to-rest ratio and did not match
the length of recovery between protocols, because shorter recovery periods would
promote a high cardiopulmonary strain during CWR despite shorter exercise
duration.

**PRACTICAL APPLICATIONS**

The main practical application of the present study was to demonstrate that
the DWR protocol seems to be an interesting strategy for increasing cardiovascular
and metabolic strain (i.e., time near $VO_{2\text{max}}$). It has been previously demonstrated
that a severe DWR training protocol based on $P_{\text{peak}}$ (i.e., from 110 to 95% $P_{\text{peak}}$)
led to robust short-term aerobic training gains in active subjects (13). In the present
study, $P_{\text{high}}$ corresponded to 129 ± 10% of $P_{\text{peak}}$ which was similar to 130 ± 10% of
$P_{\text{peak}}$ for cyclists as reported by Caputo and Denadai (10). In this way, it is possible
that intensities near 130% of $P_{\text{peak}}$ could be appropriate for severe-intensity interval
training close to the upper boundary of the severe-intensity exercise domain. A
DWR training session with each repetition begun at 130% of $P_{\text{peak}}$ applying three
progressively decreases of ~12% in exercise intensity every 30 s (i.e., 2-min exercise
bout) and a work-to-rest ratio of 1:1 could be performed when the training aim is
time at $VO_{2\text{max}}$. However, these recommendations are limited to the $P_{\text{peak}}$ obtained
during 3-min stages incremental test. For shorter incremental test (e.g., ramp test),
which would probably induced a higher $P_{\text{PEAK}}$, the appropriate modifications must be
made to allow a sufficient exercise time.

A large pool of muscle fibers might be recruited during both DWR and CWR (considering a minimal recruitment threshold at $> 75\text{–}85\%$ of $\text{VO}_{2}\text{max}$ for type II fibers) (1, 7), with the muscle activation relative to power output increasing over time (higher RMS/PO ratio) (7). However, as a decrease in RMS amplitude was observed in DWR, if a near constant RMS is intended with a DWR exercise, slower and/or lesser decreases in the work-rate could be used. Finally, while CWR protocol seems to promote important cardiorespiratory and neuromuscular adaptations following short-term training (27-29), the use of DWR could be even more relevant for such parameters based on the findings herein reported. Regardless of the work-rate manipulation strategy, the severe exercise domain can indeed be an interesting range for simultaneous cardiopulmonary and neuromuscular development.

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Acknowledgments

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**Figure 1.** Schematic illustration of the two intermittent exercise protocols (see text for further details).

**Figure 2.** Mean ± SD of EMG response (normalized RMS and normalized RMS relative to work rate – RMS/PO ratio) to decreasing work rate (DWR) and constant work rate (CWR) protocols at each repetition analysed (First, Second, and Last). In these repetitions, the RMS value was calculated using two time windows relative to the repetition duration: one from the start (Start portion) and the other from the final (Final portion). *Significant difference from DWR p < 0.05; #Significant difference from Start portion p < 0.05; **Significant difference from First repetition p < 0.05.

**Figure 3.** Group mean VO$_2$ and RMS responses to decreasing work rate (DWR; left panels) and constant work rate (CWR; right panels) protocols. The VO$_2$ values are expressed relative to VO$_2$max and RMS are expressed relative to normalization criteria (upper panels), and both VO$_2$ and RMS are expressed relative to workload (bottom panels). The x-axis is presented mean values of 5% of individual time elapsed in First, Second and Last repetition during each protocol.
TABLE 1. Incremental and constant work rate tests responses. Values are mean ± SD.

<table>
<thead>
<tr>
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<th>Mean ± SD</th>
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<tbody>
<tr>
<td><strong>Incremental test</strong></td>
<td></td>
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<tr>
<td>$P_{\text{PEAK}}$ (W)</td>
<td>334 ± 37</td>
</tr>
<tr>
<td>$\text{VO}_2\text{max}$ (mL.min$^{-1}$)</td>
<td>4702 ± 475</td>
</tr>
<tr>
<td><strong>Critical power parameters</strong></td>
<td></td>
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<tr>
<td>95%$P_{\text{PEAK}}$ time to exhaustion (s)</td>
<td>542 ± 213</td>
</tr>
<tr>
<td>110%$P_{\text{PEAK}}$ time to exhaustion (s)</td>
<td>239 ± 58</td>
</tr>
<tr>
<td>CP (W)</td>
<td>282 ± 39</td>
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<tr>
<td>Total amount of work that can be performed above CP (kJ)</td>
<td>18.3 ± 2.7</td>
</tr>
<tr>
<td><strong>Upper boundary of severe domain parameters</strong></td>
<td></td>
</tr>
<tr>
<td>$P_{\text{HIGH}}$ (W)</td>
<td>430 ± 45</td>
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<tr>
<td>$T_{\text{LOW}}$ (s)</td>
<td>124 ± 27</td>
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</tbody>
</table>

Peak power associated with the end of the incremental test ($P_{\text{PEAK}}$); The highest 15-s $\text{VO}_2$ value reached during incremental test ($\text{VO}_2\text{max}$); Time to exhaustion at 95% and 110% of $P_{\text{PEAK}}$; Critical power (CP); The highest power that still permits the achievement of maximal oxygen uptake ($P_{\text{HIGH}}$) and; The lowest exercise duration at which $\text{VO}_2\text{max}$ is attained ($T_{\text{LOW}}$).
TABLE 2. Responses to severe-intensity intermittent exercise sessions. Values are mean ± SD.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DWR</td>
</tr>
<tr>
<td>Number of repetitions (a.u)</td>
<td>5.1 ± 1.7</td>
</tr>
<tr>
<td>Bout and rest duration (s)</td>
<td>124 ± 27</td>
</tr>
<tr>
<td>Time to exhaustion (s)</td>
<td>635 ± 223</td>
</tr>
<tr>
<td>Total work (kJ)</td>
<td>229 ± 86</td>
</tr>
<tr>
<td>t95%VO₂max (s)</td>
<td>323 ± 227</td>
</tr>
<tr>
<td>t95%VO₂max (% Time to exhaustion)</td>
<td>48 ± 18</td>
</tr>
<tr>
<td>Total amount of O₂ consumed (L·kg⁻¹)</td>
<td>0.97 ± 0.41</td>
</tr>
<tr>
<td>Peak minute ventilation (L·min⁻¹)</td>
<td>167 ± 29</td>
</tr>
<tr>
<td>Peak respiratory frequency (breaths min⁻¹)</td>
<td>65 ± 8</td>
</tr>
<tr>
<td>Peak heart rate (beats min⁻¹)</td>
<td>185 ± 7</td>
</tr>
<tr>
<td>pH (a.u)</td>
<td>7.13 ± 0.04</td>
</tr>
<tr>
<td>Blood lactate concentration (mmol L⁻¹)</td>
<td>13.1 ± 1.9</td>
</tr>
</tbody>
</table>

Number of repetitions completed and its proportion; time spent at or above 95%VO₂max (t95%VO₂max); pH and blood lactate responses at moment of exhaustion in decreasing work rate (DWR) and constant work rate (CWR).

*Significant difference from DWR.