Muscle metabolic responses during high-intensity intermittent exercise measured by 31P-MRS: relationship to the critical power concept

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Chidnok W, DiMenna FJ, Fulford J, Bailey SJ, Skiba PF, Vanhatalo A, Jones AM. Muscle metabolic responses during high-intensity intermittent exercise measured by 31P-MRS: relationship to the critical power concept. Am J Physiol Regul Integr Comp Physiol 305: R1085–R1092, 2013. First published September 25, 2013; doi:10.1152/ajpregu.00406.2013.—We investigated the responses of intramuscular phosphate-linked metabolites and pH (as assessed by 31P-MRS) during intermittent high-intensity exercise protocols performed with different recovery-interval durations. Following estimation of the parameters of the power-duration relationship, i.e., the critical power (CP) and curvature constant (W), for severe-intensity constant-power exercise, nine male subjects completed three intermittent exercise protocols to exhaustion where periods of high-intensity constant-power exercise (60 s) were separated by different durations of passive recovery (18 s, 30 s and 48 s). The tolerable duration of exercise was 304 ± 68 s, 516 ± 142 s, and 847 ± 240 s for the 18-s, 30-s, and 48-s recovery protocols, respectively (P < 0.05). The work done >CP (W>CP) was significantly greater for all intermittent protocols compared with the subjects’ W, and this difference became progressively greater as recovery-interval duration was increased. The restoration of intramuscular phosphocreatine concentration during recovery was greatest, intermediate, and least for 48 s, 30 s, and 18 s of recovery, respectively (P < 0.05). The W>CP in excess of W increased with greater durations of recovery, and this was correlated with the mean magnitude of muscle phosphocreatine reconstitution between work intervals (r = 0.61; P < 0.01). The results of this study show that during intermittent high-intensity exercise, recovery intervals allow intramuscular homeostasis to be restored, with the degree of restoration being related to the duration of the recovery interval. Consequently, and consistent with the intermittent CP model, the ability to perform W>CP during intermittent high-intensity exercise and, therefore, exercise tolerance, increases when recovery-interval duration is extended.

critical power; W, exercise tolerance; interval training; fatigue; performance; intermittent exercise

THE PHYSIOLOGICAL RESPONSES during constant-power-output exercise are highly predictable depending upon the intensity domain in which an individual is exercising, with the differences in pulmonary gas exchange, blood acid-base, and muscle metabolic profiles being well described (21, 23, 33, 43, 44). The critical power (CP) represents the upper boundary of the heavy-intensity exercise domain, within which a physiological steady state can be achieved. In contrast, exercise in the severe-intensity domain (above CP), is characterized by the development of a “slow component” that drives VO2 to its maximum and an inability to achieve steady states in, for example, muscle phosphocreatine concentration ([PCr]) and blood [lactate]. The CP is defined as the asymptote of the hyperbolic relationship between power (P) and the limit of exercise tolerance (Tlim), while the curvature constant of this hyperbola (W) represents a fixed amount of work that can be performed above CP (14, 22, 30, 31). It is apparent that depletion of the W and the development of the VO2 slow component occur concomitantly such that Tlim ultimately depends upon the interaction between the W and the magnitude and trajectory of the VO2 slow component, in addition to the “ceiling” imposed by VO2max (6, 20, 41).

High-intensity interval training (HIIT), i.e., repetitions of relatively brief bouts of exercise performed with “all-out” effort, or at an intensity close to that which elicits VO2max, interspersed with periods of rest or lower-intensity exercise, is an effective way to improve aerobic fitness (10, 16, 26, 27). However, the specific protocol required to achieve maximum benefit from HIIT (e.g., the intensity, number and duration of “work” intervals, and the duration of, and activity pattern during, recovery intervals) remains to be determined. In this regard, it is interesting that the CP concept has recently been applied to intermittent exercise (5, 7, 32). It may be important to consider the utilization and reconstitution of W during intermittent exercise, along with the possible physiological determinant(s) of W, when prescribing HIIT variables.

It has been reported that for exercise to be continued immediately following the attainment of Tlim, the P must be reduced <CP (8, 9). We have shown that when repeated 60-s severe-intensity cycling bouts are separated by 30-s recovery intervals where P is below CP, the W is partially restored, and Tlim is extended; in contrast, when the recovery P remains above CP, the W continues to be expended, albeit at a slower rate (7). In that study, the intensity of the <CP recovery was inversely related to the magnitude of W restoration between the high-intensity exercise bouts, and also to the rates of change of W, VO2 and the integrated electromyogram to their minimum/maximum values recorded at the limit of tolerance (7). Collectively, these studies indicate that the extent of W recovery between high-intensity exercise bouts is related to the intensity of the recovery activity (7, 9). Presumably, the magnitude of W restoration should also be a function of the duration of the recovery interval, although this has not been investigated.
Muscle metabolic responses during, and in the recovery from, high-intensity exercise can be assessed noninvasively and with high temporal resolution using $^3$P-magnetic resonance spectroscopy ($^3$P-MRS). It has been established that the relative changes in energy metabolites as measured by $^3$P-MRS closely reflect those measured biochemically from muscle biopsy samples (2). We have recently reported that, following $T_{\text{lim}}$, recovery exercise at a $P$ that is below $CP$ allows muscle phosphocreatine concentration ([PCr]) and pH to increase from the low values achieved at $T_{\text{lim}}$ and inorganic phosphate concentration ([Pi]) and ADP concentration ([ADP]) to fall from the peak values achieved at $T_{\text{lim}}$; in contrast, when the recovery exercise is performed above $CP$, no such muscle metabolic recovery is evident (8). These results are consistent with the notion that replenishment of intramuscular substrates and/or clearance of fatigue-related metabolites (23, 39). However, it is not known how changes in intramuscular high-energy phosphate compounds and related metabolites during high-intensity intermittent exercise with different durations of passive recovery might relate to $W'$ and exercise tolerance.

The purpose of this investigation was, therefore, to determine the responses of intramuscular phosphate-linked variables ([PCr], [Pi], and [ADP]) and pH during intermittent high-intensity exercise protocols performed with recovery intervals (passive rest) of different duration. We hypothesized that, during an exhaustive intermittent knee-extension exercise protocol in which 60-s work intervals were separated by either 18-s, 30-s, or 48-s recovery intervals, the total amount of work completed above $CP$ ($W_{>CP}$) would be greater than $W'$ estimated from a series of constant-$P$ bouts. We also hypothesized that $W_{>CP}$ and $T_{\text{lim}}$ would be greatest/longest, intermediate, and least/shortest for the protocols that used the 48-s, 30-s, and 18-s recovery intervals, respectively, and that differences in $W_{>CP}$ and $T_{\text{lim}}$ among conditions would be related to the extent of [PCr] reconstitution in the recovery intervals between work bouts. Finally, we hypothesized that, despite differences in $T_{\text{lim}}$ in the different recovery conditions, the limit of tolerance for all three conditions would be associated with similar values for [PCr], [Pi], [ADP], and pH.

METHODS

Subjects. Nine male subjects (means ± SD: age 22 ± 3 yr, stature 1.75 ± 0.04 m, body mass 76 ± 10 kg) volunteered and gave written informed consent to participate in this study, which had been approved by the University of Exeter Research Ethics Committee. The subjects were all recreationally active and were familiar with the experimental procedures used in the study. On test days, subjects were instructed to report to the laboratory in a rested state, having completed no strenuous exercise or consumed alcohol within the previous 24 h, and having abstained from food and caffeine for the preceding 3 h. Testing was conducted at the same time of day (±2 h) for each subject, and laboratory visits were separated by at least 48 h.

Experimental overview: This study was conducted in two parts. Initially, the power-duration relationship for single-leg knee-extension exercise was established for each subject from four separate exercise bouts. From this relationship, the $CP$ and $W'$ were estimated. Subsequently, using the same ergometer, the subjects performed a single-leg knee-extension intermittent exercise protocol to exhaustion with simultaneous interrogation of muscle energetics using $^3$P-MRS. Muscle metabolites ([PCr], [Pi], and [ADP]) and pH were assessed continuously during the protocol within which intervals of high-intensity constant-$P$ exercise (60 s) were separated by three different durations of passive recovery intervals (18-s, 30-s, and 48-s), which were presented to subjects in a randomized order. Passive rather than active recovery was selected in the present study because the exercise ergometer requires manual alteration of basket loading, which may have introduced error especially in the condition with the shortest recovery time. The recovery intervals were selected to provide total exercise times ranging from ~4 to ~18 min. In total, the subjects made seven visits to the laboratory, and the entire protocol was completed within 15–25 days for each subject.

PART I: estimation of $CP$ and $W'$. The subjects initially completed four severe-intensity prediction trials at different constant $P$ to determine the hyperbolic $P-CP$ relationship. The $P$ for the trials was selected, on the basis of pilot work, to yield a range of $T_{\text{lim}}$ varying from ~2 min for the shortest trial to ~12 min for the longest trial (39). The single-leg knee-extension exercise bouts were completed on separate days and presented in randomized order. Subjects were placed in a prone position and secured to the ergometer bed with Velcro straps at the thigh, buttocks, and lower back to minimize extraneous movement during the exercise protocol. The ergometer consisted of a nylon frame secured on top of the bed close to the subject’s feet and a base unit placed at the distal end of the bed. The subject’s right foot was connected to a rope running along the top of the frame to the base unit, on which a mounted pulley system permitted brass weight plates to be lifted and lowered. Exercise was performed at the rate of 40 contractions/min, with the subject lifting and lowering the weight over a distance of ~0.22 m, in accordance with a visual cue presented on a monitor and an audible cue timed to the bottom of the down stroke. A shaft encoder (type BDK-66; Baumer Electrics, Swindon, UK) was fitted within the pulley system to record the distance traveled by the load, alongside a nonmagnetic load cell (type FS250; Novatech Measurements, St. Leonards-on-Sea, UK) to record applied force, which was then used to calculate the work rate. The test-retest reliability of the work done within a bout of exercise is <5% on this ergometer.

During all exhaustive tests, the subjects were verbally encouraged to continue exercising for as long as possible. The $T_{\text{lim}}$, which was defined as the time at which the subject could no longer keep pace with the required rate of muscle contraction, was recorded to the nearest second. Subjects were not informed of the $P$ or their $T_{\text{lim}}$ values until the entire project had been completed. Individual $CP$ and $W'$ estimates were derived from the four prediction trials by least-squares fitting of the following regression models:

1) Nonlinear power ($P$) vs. time ($T$):

$$W' = W' / (P - CP)$$

2) Linear work ($W$) vs. time model:

$$W = CP \times T + W'$$

3) Linear power ($P$) vs. 1/time model:

$$P = (1/T) \times W' + CP$$

The parameter estimates from Eqs. 1–3 were compared to ensure goodness of fit, and the model with the lowest standard error of the estimate (SEE) was chosen for further analysis.

PART II: $^3$P-MRS assessment of muscle metabolic responses to high-intensity intermittent exercise. After completion of the prediction trials for estimation of the $CP$ and $W'$, the subjects reported to the MRS laboratory at the Exeter Magnetic Resonance Research Unit on three separate occasions within 7–10 days. Exhaustive intermittent exercise protocols were performed with simultaneous measurement of muscle metabolic responses by $^3$P-MRS using a 1.5-T superconducting magnetic resonance scanner (Intera, Philips, Amsterdam, the Netherlands) and using the same ergometer and experimental setup, as described in Part I. To collect the $^3$P-MRS data during the protocol, a 6-cm $^3$P transmit/receive surface coil was placed within the ergom-
eter bed, and the subject was positioned such that the coil was centered over the quadriceps muscle of the right leg. Initially, fast-field echo images were acquired to determine correct positioning of the muscle relative to the coil. Cod liver oil capsules were placed in the scanner bed adjacent to the location of the coil. As the capsules generate high-intensity signals in the initial survey images, they allowed confirmation that the quadriceps had been centered directly over the coil.

A number of preacquisition steps were carried out to optimize the signal from the muscle under investigation. Tuning and matching of the coil were performed to maximize energy transfer between the coil and the muscle. An automatic shimming protocol was then undertaken within a volume that defined the quadriceps muscle to optimize homogeneity of the local magnetic field, thereby leading to maximal signal collection.

Subjects were required to perform single-leg knee-extension exercise using three intermittent protocols, where periods of high-intensity exercise (60 s) were separated by different durations of passive recovery intervals. Recovery-interval durations for the three conditions were 18 s, 30 s, and 48 s, and all bouts were continued to Tmax, which was defined and recorded as it was for Part I (see Part I: estimation of CP and W'). The high-intensity P for the work intervals of these protocols was calculated using the CP and W' estimates from Part I, according to the intermittent CP model (Eq. 4, Ref. 32) to provide a P that was predicted to elicit exhaustion after ~4, 6, and 8 completed work/recovery cycles (i.e., after 312 s, 540 s, and 864 s of intermittent exercise) for the 18-s, 30-s, and 48-s recovery conditions, respectively:

\[ T_{\text{lim}} = n(t_w + t_r) + \left[ W' - n\{P_w - CP\}P_w - (CP - P_r)t_r\right] / (P_w - CP) \]  

where \( T_{\text{lim}} \) is total protocol time, n is the number of completed work/recovery cycles, \( t_w \) and \( t_r \) are the durations, and \( P_w \) and \( P_r \) are the P for the work and recovery intervals, respectively, and \( P_w > CP \). The three protocols were undertaken on separate days in randomized order.

During the entire exercise and recovery periods, \(^{31}\text{P-MRS} \) data were acquired every 1.5 s with a spectral width of 1.500 Hz and 1,000 data points. Phase cycling with four phase cycles was used, leading to a spectrum being acquired every 6 s. The subsequent spectra were quantified by peak fitting, with the assumption of prior knowledge, using the AMARES fitting algorithm in the jMRUI (version 3) software package. Spectra were fit with the assumption that Pi, PCR, ATP, and phosphodiester peaks were present. In all cases, relative amplitudes were corrected for partial saturation due to the repetition time relative to \( T_1 \) relaxation time. The \( T_1 \) saturation was corrected via a spectrum that was acquired with a long relaxation time prior to the beginning of data acquisition.

Intracellular pH was calculated using the chemical shift of the Pi spectra relative to the PCR peak (37). The [PCR] and [Pi] were expressed as a percentage change relative to resting baseline (i.e., prior to initiation of the protocol), which was assumed to represent 100%. The [ADP] was calculated as described by Kemp et al. (25).

Data analysis procedures. To estimate the work done above CP (\( W_{>CP} \), expressed in kilojoules) during the intermittent exercise protocols, we used the following equation:

\[ W_{>CP} = \left[ (P_w \times t_w) - (CP \times t_w) \right] / 1000 \]  

where \( P_w \) is the high-intensity P, \( t_w \) is the cumulative time spent at \( P_w \) during the intermittent protocol, and CP is the critical power.

Baseline values for [PCR], [Pi], [ADP], and pH were defined as the mean values measured over the initial 120 s of rest (i.e., prior to initiation of the first high-intensity work interval), while end-exercise values for these variables were defined as the mean values measured over the final 18 s of exercise. The changes in [PCR], [Pi], [ADP], and pH across the protocol (\( \Delta \) [PCR], \( \Delta \) [Pi], \( \Delta \) [ADP], and \( \Delta \) pH) were then calculated as the difference between end-exercise and baseline values.

For each recovery interval, the prerecovery [PCR] (\( [\text{PCR}_{\text{pre}}] \)) was defined as the value measured during the final 6 s of the preceding work interval, and the end-recovery [PCR] (\( [\text{PCR}_{\text{end}}] \)) was defined as the value measured during the final 6 s of that specific recovery interval. The amplitude of [PCR] restoration during each recovery interval was then calculated as the difference between [PCR] in and [PCR] out. These values were calculated for all completed intervals and averaged across each intermittent protocol to provide the mean [PCR] restoration amplitude for each condition.

In addition to calculating the magnitude of [PCR] restoration for each protocol, we were also interested in comparing the time course of [PCR] restoration across both protocol (e.g., for the 48-s recovery interval compared with the 18-s recovery interval) and time (e.g., for the final recovery interval compared with the initial recovery interval). However, quantifying the response by fitting it with the higher-order model that would likely be necessary under these conditions (13) was not possible due to the short recovery intervals (i.e., only four points were available in the 18-s recovery condition). We deemed that the most appropriate strategy was to fit the [PCR] data over the same time window for each of the protocols. Consequently, we determined a [PCR] restoration “mean response time” (MRT) for the initial and final recovery interval (i.e., MRT, and MRTf, respectively) of each protocol by fitting the first four data points collected during the recovery interval with a single exponential function with the amplitude term fixed based on the assumption that full restoration (i.e., restoration to the baseline value of 100%) would occur. The first four [PCR] data points during the initial and final recovery interval for each protocol were fit with an exponential function of the form:

\[ [\text{PCR}] = [\text{PCR}]_{\text{pre}} + [\text{PCR}]_{\alpha} \left( 1 - \exp^{-t / \text{MRT}} \right) \]  

where [PCR] is the [PCR] at any given time t during the recovery interval, [PCR]pre is the [PCR] prior to initiating the recovery interval, [PCR]α is the [PCR] amplitude that would be required for full restoration (i.e., 100–[PCR]pre), and MRT is the [PCR] mean response time. Statistical analysis. One-way ANOVA was used to compare CP and W among the three models. One-way repeated-measures ANOVA were employed to determine differences among the three intermittent protocols for the \(^{31}\text{P-MRS} \) data ([PCR], [Pi], [ADP], and pH), \( T_{ \text{lim} } \), and \( W_{>CP} \). A two-way repeated-measures ANOVA was used to assess differences in [PCR]MRT between the first and last recovery intervals across the three intermittent protocols. Where the analysis revealed a significant difference, simple contrasts with Fisher’s least significant difference were used to determine the origin of such effects. The relationship between the \( W_{>CP} \) and the mean magnitude of muscle [PCR] restoration between work intervals was calculated using the Pearson product moment correlation coefficient. All data are presented as means ± SD. Statistical significance was accepted when \( P < 0.05 \).

RESULTS

All subjects completed the four constant-P exercise trials for the estimation of the CP and W (i.e., see Part I: estimation of CP and W). There were no significant differences among models for the CP estimates (16 ± 4 W, 17 ± 4 W, and 15 ± 4 W for models 1, 2, and 3, respectively; \( P > 0.05 \)) or for the W estimates (1.90 ± 0.67 kJ, 1.83 ± 0.64 kJ, and 2.16 ± 0.74 kJ for models 1, 2, and 3, respectively; \( P > 0.05 \)). Model 3 had the lowest SEE and was used to calculate the high-intensity P for the work intervals used in the intermittent protocols, i.e., \( P_w \) derived via Eq. 4, which was 33 ± 7 W.

Table 1 presents the values for \( T_{\text{lim}} \) and \( W_{>CP} \), and the \(^{31}\text{P-MRS} \) data for the three high-intensity intermittent exercise protocols. \( T_{\text{lim}} \) was significantly different among the three protocols. Specifically, \( T_{\text{lim}} \) was 304 ± 68 s for the high-
Table 1. Selected muscle metabolite responses and limit of tolerance during intermittent high-intensity exercise protocols with different recovery durations

<table>
<thead>
<tr>
<th></th>
<th>18 s</th>
<th>30 s</th>
<th>48 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-exercise [PCr], % of baseline</td>
<td>40 ± 10</td>
<td>40 ± 8</td>
<td>44 ± 10</td>
</tr>
<tr>
<td>Δ[PCr], %</td>
<td>60 ± 10</td>
<td>60 ± 8</td>
<td>56 ± 11</td>
</tr>
<tr>
<td>End-exercise [P], % of baseline</td>
<td>592 ± 285</td>
<td>519 ± 218</td>
<td>555 ± 236</td>
</tr>
<tr>
<td>Δ[P], %</td>
<td>492 ± 285</td>
<td>419 ± 218</td>
<td>455 ± 236</td>
</tr>
<tr>
<td>Baseline [ADP], μM</td>
<td>6 ± 3</td>
<td>6 ± 2</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>End-exercise [ADP], μM</td>
<td>65 ± 24</td>
<td>72 ± 52</td>
<td>69 ± 37</td>
</tr>
<tr>
<td>Δ[ADP], μM</td>
<td>58 ± 23</td>
<td>66 ± 51</td>
<td>64 ± 37</td>
</tr>
<tr>
<td>Baseline pH</td>
<td>7.0 ± 0</td>
<td>7.0 ± 0</td>
<td>7.0 ± 0</td>
</tr>
<tr>
<td>End-exercise pH</td>
<td>6.6 ± 0.2</td>
<td>6.6 ± 0.2</td>
<td>6.6 ± 0.2</td>
</tr>
<tr>
<td>ΔpH</td>
<td>0.4 ± 0.1</td>
<td>0.4 ± 0.2</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>[PCr] restoration amplitude, %</td>
<td>13 ± 5</td>
<td>21 ± 4*</td>
<td>27 ± 7*</td>
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<tr>
<td>[PCr] restoration MRTi, s</td>
<td>67 ± 30</td>
<td>60 ± 16</td>
<td>62 ± 16</td>
</tr>
<tr>
<td>[PCr] restoration MRTf, s</td>
<td>71 ± 26</td>
<td>62 ± 8</td>
<td>78 ± 26</td>
</tr>
<tr>
<td>Tlim, s</td>
<td>304 ± 68</td>
<td>516 ± 142a</td>
<td>847 ± 240b</td>
</tr>
<tr>
<td>Time spent above CP, s</td>
<td>244 ± 53</td>
<td>359 ± 93a</td>
<td>494 ± 134ab</td>
</tr>
<tr>
<td>W&lt;sub&gt;–CP&lt;/sub&gt;, kJ</td>
<td>3.8 ± 1.0</td>
<td>5.6 ± 1.8b</td>
<td>7.9 ± 3.1b</td>
</tr>
</tbody>
</table>

*Significantly different from 18 s (P < 0.05). †Significantly different from 30 s (P < 0.05). [PCr], phosphocreatine concentration; [P], inorganic phosphate concentration; [ADP], calculated adenosine diphosphate concentration; MRTi, mean response time for initial recovery interval; MRTf, mean response time for final recovery interval; Tlim, limit of exercise tolerance; W<sub>–CP</sub>, amount of work completed above CP.

The principal original finding of this investigation was that the W<sub>–CP</sub> in excess of W′ became progressively greater, and limit of tolerance became progressively longer, as recovery-interval duration was increased during exhaustive intermittent high-intensity exercise. The increase in W<sub>–CP</sub> in excess of W′, with greater durations of recovery, was correlated significantly with the amplitude of muscle [PCr] reconstitution between work intervals. At the limit of tolerance, there were no significant differences in the measured high-energy phosphate compounds or metabolites ([PCr], [ADP], [P], and [H<sup>+</sup>]) among the protocols. These results are consistent with our hypotheses and indicate that longer recovery intervals during high-intensity intermittent exercise delay the attainment of the “limiting” intramuscular environment that is associated with the attainment of the limit of tolerance (23, 39).

The physiological responses to repeated high-intensity exercise have been investigated previously (1, 15, 17), and the muscle metabolic changes invoked close to the termination of exercise and in subsequent recovery have been assessed at discrete time points using muscle biopsy (4, 11, 15). However, to our knowledge, this is the first study to use 31P-MRS to investigate the dynamic responses of high-energy phosphate intensity intermittent protocol that employed the 18-s recovery intervals, 516 ± 142 s (i.e., ~69% longer) for the protocol with the 30-s recovery intervals (P < 0.05) and 847 ± 240 s (i.e., ~179% longer) for the protocol with the 48-s recovery intervals (P < 0.05). The actual Tlim values were not significantly different from the values of Tlim predicted using Eq. 4. The total exercise time above CP (i.e., neglecting the recovery intervals) was also significantly different (P < 0.05) between the three protocols: 244 ± 53 s for the 18-s recovery intervals, 359 ± 93 s for the 30-s recovery intervals, and 494 ± 134 s for the 48-s recovery intervals. W<sub>–CP</sub> and [PCr] restoration amplitude also became progressively greater as recovery-interval duration was increased with all three values being significantly different from one another (Table 1). Furthermore, W<sub>–CP</sub> for all three intermittent protocols was greater than the W′ estimated from the conventional constant-P trials (P < 0.05).

The [PCr]<sub>MRT</sub> was not significantly different across protocols for either the initial or final recovery interval. However, two-way ANOVA revealed a significant main effect by time, indicating that, across protocols, the [PCr]<sub>MRT</sub> was lengthened (i.e., [PCr] restoration kinetics were slower) during the final compared with the initial recovery interval (P < 0.01). The increase in W<sub>–CP</sub> above W′ with greater durations of recovery was significantly correlated with the mean amplitude of muscle [PCr] reconstitution between work intervals (r = 0.61; P < 0.01).

[PCr] and pH displayed a “saw-tooth” response profile commensurate with the work and recovery intervals but with the peaks and troughs in pH lagging those of [PCr] by ~20 s (Figs. 1, 2, and 3). The responses were similar in all nine subjects. There were no significant differences in baseline, end-exercise or Δ values among protocols for any of the intramuscular variables measured via 31P-MRS. For example, [PCr] at Tlim was ~40% of the preprotocol value, and pH was ~6.6, regardless of the recovery-interval duration employed (Table 1 and Figs. 1–3).
compounds and metabolites to high-intensity intermittent exercise with different recovery durations. The results are consistent with the CP model of bioenergetics, which describes a two-component system comprising an oxidative component that is theoretically limited in rate but unlimited in capacity (CP), and a supplementary component (W') that reflects a finite capacity to perform work above CP (22). Intrinsic to the CP concept is that, while W' can be expended at different rates, the limit of tolerance for all constant-P exercise above CP will coincide with the complete depletion of W'. We have previously confirmed that this concept also applies during intermittent exercise, in which high-intensity work intervals are interspersed with lower-intensity recovery intervals (7). Specifically, W' > CP can be increased and T_{lim} extended if recovery intervals are performed at a P that allow some degree of W' recharge (i.e., work rates below CP) (7, 36). In the present study, we investigated the intramuscular determinants of this phenomenon by measuring metabolic changes during repeated 60-s, high-intensity exercise bouts, separated by relatively short passive recovery intervals (i.e., 18 s, 30 s, and 48 s, giving work-recovery ratios of 3.3:1, 2:1, and 1.25:1, respectively) to permit W' repletion. In all three conditions, the W' > CP was greater than the W', indicating that W' repletion had occurred during the intermittent protocols, with the W' > CP being greatest for the longest recovery interval and least for the shortest recovery interval.

We used 31P-MRS to measure intramuscular metabolic responses during the three intermittent exercise protocols and found that, regardless of recovery-interval duration or total tolerable exercise time (between ~4 min and ~16 min), the values for intramuscular high-energy phosphate compounds and metabolites were similar at the point of exhaustion. For all three protocols, [PCR] had decreased to ~40% of its preexercise value, pH had dropped from ~7.0 to ~6.6, and P_i had increased more than five-fold, at the limit of tolerance. These findings are consistent with the notion that W', and the limit of tolerance, are related to the depletion/accumulation of one or more substrates/metabolites, which are linked to the process of muscle fatigue (22, 23, 39). We cannot determine which of these changes (for example, low [PCR], low pH, or high [P_i]) is most influential in preventing the continuation of exercise; indeed, the inability to continue exercise might be related to a “composite” change in the muscle metabolic milieu, which directly or indirectly impairs muscle function. It might be considered surprising that exercise intolerance occurred when
~40% of the resting muscle [PCr] was still available. However, it is important to remember that this value represents the “mean” [PCr] in the region of muscle interrogated by MRS. It has been demonstrated that the depletion of muscle high-energy phosphates during exercise is heterogeneous (35), such that “global” fatigue during exercise might be attributed to reduced force production in a relatively small population of muscle fibers (35). We have previously shown that recovery of [PCR], pH, and [Pi] following exhaustive severe-intensity exercise depends on whether subsequent recovery exercise is performed below or above the CP (8). In the present study, the 48-s recovery interval provided the greatest opportunity for partial recovery of these variables, which explains why the greatest augmentation of W > CP and, therefore, Tlim was observed for this condition. These results are consistent with earlier studies, which reported that multiple-sprint cycling performance is improved when longer recovery durations are permitted between sprints (17) and that fatigue development during such exercise is linked, in part, to muscle [PCr], as measured by muscle biopsy (4, 15).

The mean amplitude of [PCr] restoration during the 48-s recovery intervals was approximately twice that which was present when 18-s periods of recovery were allowed. Interestingly, W > CP during the entire protocol using the 48-s recovery intervals was also approximately doubled (see Table 1). Indeed, the increase in W > CP in excess of W’ with greater durations of recovery was significantly correlated with the amplitude of muscle [PCr] reconstitution between work intervals. While the precise physiological determinants of W’ remain to be determined, this finding is consistent with some earlier studies that indicate that muscle [PCr] may contribute to the W’ (29, 40). A consistent feature of supra-CP exercise is that VO2 rises inexorably (due to the presence of a VO2 “slow component”), such that once Tlim is attained (and, therefore, W’ is “zero”), VO2 max is attained (18). The kinetics of pulmonary VO2 is similar to that of muscle [PCr] (23, 34), with this link being consistent with feedback control of oxidative phosphorylation (28). Although, for technical reasons, we did not measure VO2 in the present study, it is interesting that the dynamics of [PCr] that we observed (Figs. 1–3) are similar to the dynamics of VO2 during intermittent exercise that we reported in an earlier study (see Fig. 2 in Ref. 7). Specifically, longer recovery intervals (present study) or lower intensities of recovery exercise (7), during intermittent exercise blunt the overall rate at which [PCr] falls toward the value that is associated with exercise intolerance and simultaneously blunt the rate at which VO2 increases toward its maximum value. It should be noted that muscle [PCr] dynamics might only represent a proxy for other intramuscular changes (for example, in [ADP], [Pi], or metabolites that were not measured in the present study) that might contribute to fatigue development and/or respiratory control. It is clear, however, that the nature of the recovery interval influences the extent of the muscle metabolic perturbation and the rate of fatigue development and, in turn, impacts the cardiorespiratory responses to intermittent exercise.

In addition to assessing the amplitude of [PCr] restoration during the recovery intervals employed in the present study, we also characterized the [PCr] restoration time course. Unfortunately, the relatively short periods of recovery limited the data available for modeling the response. Consequently, we could not use the higher-order model that would typically be required for this type of exercise (e.g., Ref. 13), and our results should, therefore, be interpreted with due caution. However, the [PCr]MRT was not significantly different between the three conditions, but did become longer for all conditions as the intermittent exercise proceeded (i.e., for the final recovery interval compared with the initial one). This slowing of the [PCr] recovery dynamics during intermittent exercise as the baseline metabolic rate was increased (as may be inferred from the lower-end recovery interval [PCr]) is consistent with the study of Skiba et al. (36). These authors reported that W’ recovery between high-intensity exercise bouts was faster at lower recovery P, and, therefore, lower-recovery metabolic rates.

Perspectives and Significance

In practical terms, the slowing of [PCr] restoration as the intermittent protocol continued (which is likely, at least in part, a consequence of the progressive decline in pH; Refs. 19 and 38) is important to consider when prescribing HIIT recovery-interval variables. Specifically, if the goal is to provide a consistent degree of [PCr] restoration prior to initiating a subsequent work interval, the recovery-interval duration should be progressively lengthened over the course of the HIIT session. Although intuitive, the results of the present study also clearly show, for the first time, that longer recovery intervals during intermittent exercise permit a greater recovery of intramuscular high-energy phosphate compounds and metabolites, and, therefore, facilitate the completion of more work intervals. This helps to provide the scientific rationale for coaches, athletes, and scientists to construct HIIT protocols that elicit specific physiological effects. From an applied science perspective, it is also pertinent to note that the intermittent CP model (32) permitted an accurate prediction of the tolerable duration of intermittent exercise for all three recovery-interval conditions. This indicates that the CP model might be valuable in the individualized prescription of HIIT variables which, over the longer term, might optimize gains in fitness and performance.

In conclusion, the muscle metabolic responses and exercise tolerance during high-intensity intermittent exercise protocols using recovery intervals of different durations can be explained in accordance with the CP model of bioenergetics. Specifically, when an interval of passive rest (e.g., for 18 s) is interspersed between 60-s intervals of high-intensity exercise, W > CP is greater than the W’ measured during constant-P exercise. Furthermore, when recovery-interval duration is extended (e.g., to 30 s and 48 s), the W > CP is progressively increased, which allows Tlim to be further extended. The greater W > CP with longer recovery-interval duration was related to the extent of [PCr] reconstitution between work intervals. However, regardless of recovery-interval duration, similar values for 31P-MRS-measured variables (i.e., [PCr], [Pi], [ADP], and pH) were present at exhaustion. The duration of the recovery interval during exhaustive HIIT clearly modulates the rate at which intramuscular homeostasis is lost with implications for the tolerable duration of exercise.

GRANTS

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