Effects of prior very-heavy intensity exercise on indices of aerobic function and high-intensity exercise tolerance

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Ferguson C, Whipp BJ, Cathcart AJ, Rossiter HB, Turner AP, Ward SA. Effects of prior very-heavy intensity exercise on indices of aerobic function and high-intensity exercise tolerance. J Appl Physiol 103: 812–822, 2007. First published May 31, 2007; doi:10.1152/japplphysiol.01410.2006.—A recent bout of high-intensity work that lies between θL and critical power (CP, i.e., the power asymptote of the power-duration (P-t) relationship), the emergence of an additional delayed “slow component” (VO2sc) results in VO2 attaining an eventual steady-state value greater than that predicted from the sub-θL VO2-work rate relationship (reviewed in Refs. 24, 55), and whose origin has been demonstrated to reside predominantly within the working musculature (39, 43, 46). CP is thought to be equivalent to the highest work rate for which a steady-state VO2, [L−1]a, and acidic pHa can be achieved [22, 40, 55; although see Housh et al. (23) for an alternative view] and may, therefore, be regarded as reflecting a rate of aerobic energy pool reconstitution that dictates the maximum power that can be sustained without a progressively increasing anaerobic contribution (35, 40, 56). Above CP, VO2 continues to increase to or toward VO2max (7, 13), with the limit of tolerance typically attained when VO2max is reached or soon thereafter (reviewed in Ref. 55). Supra-CP work rates that manifest a clearly discernible VO2sc have been termed very-heavy intensity, while even higher work rates for which the fundamental VO2 requirement exceeds VO2max without manifesting a slow component have been described as being of severe intensity (reviewed in Refs. 24, 55).

The tolerable duration of supra-CP exercise (t) has been well described by a hyperbolic function of the external power (e.g., 35, 40, 56), i.e., WR = (W′/t) + CP, where W′ is the curvature constant, mathematically equivalent to a constant amount of work that can be performed above CP, independent of work rate. Some investigators consider W′ to be synonymous with the maximum O2 deficit or anaerobic work capacity (e.g., 21, 35), reflective of an anaerobic intramuscular energy store of finite capacity, comprised of high-energy phosphates, a source related to anaerobic glycolysis and the consequent production and accumulation of lactate, and the utilization of previously stored O2 (e.g., 35, 40). It has been suggested that this store is depleted at a rate proportional to the magnitude of the power requirement above CP (35, 40). Indeed observations that W′ can be influenced by interventions such as creatine loading to elevate muscle phosphocreatine concentration ([PCr]; Refs. 33, 51) and depletion of muscle glycogen stores (34) are consistent with this suggestion. An alternative scenario is that the limit of tolerance results from a build-up of fatigue-related metabolites

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such as hydrogen ions (H^+; reviewed in Ref. 14), di-protonated inorganic phosphate (H_2PO_4^-; reviewed in Refs. 1, 54) and potassium ions (K^+; reviewed in Ref. 30); or of factors proportionally coupled to them, resulting in impaired calcium handling [e.g., via alterations in Ca^{2+} release from the sarcoplasmic reticulum, Ca^{2+} myofilibril sensitivity, and maximum Ca^{2+}-activated tension (reviewed in Refs. 1, 54)], reduced muscle contractility [consequent to the accumulation of these metabolites influencing Ca^{2+} binding to troponin C (reviewed in Ref. 1, 54)] and the production of limiting "exertional" symptoms, with the rate of metabolite build-up being proportionally related to the rate of W' utilization (13).

The widespread demonstration that prior high-intensity exercise can alter the VO_2 response kinetics of subsequent high-intensity exercise is therefore of considerable interest with regard to exercise tolerance. That is, the prominence of the VO_2sc and the CP (13, 16) or an increase in anaerobic function; for example, reduced exercise tolerance. That is, the prominence of the VO_2sc and the CP (13, 16) or an increase in

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manifest through reductions in parameters of P-t relationship (i.e., CP and W') and reduced CP (13, 16) or an increase in ΔVO_2/ΔWR (48) leading to the more rapid attainment of VO_2max.

**METHODS**

**Subjects**

Six healthy, recreationally active men (age 23 ± 4.5 yr; height 178.3 ± 6.8 cm; weight 79.4 ± 11.5 kg) volunteered to participate in the study and provided written informed consent. The study was approved by the School of Biomedical Sciences/School of Sport and Exercise Sciences (University of Leeds) Ethical Review Committee, and all procedures were conducted in accordance with the Declaration of Helsinki. Prior to all experimental sessions, subjects were asked to refrain from participating in strenuous physical activity in the preceding 24 h, ingesting alcohol in the preceding 48 h, and ingesting food and caffeine in the preceding 3 h.

**Equipment**

All tests were conducted on a computer-controlled, electromagnetically braked cycle ergometer with cadence-independent work rate control (Excalibur Sport, Lode BV, Groningen, The Netherlands), calibrated periodically with a motor-driven torque calibrator (model 17800, VacuMed, Ventura, CA). Subjects breathed through a mouth-piece connected to a low dead space (0.090 liter), low-resistance (<1.5 cmH_2O at 3 l/s), turbine volume transducer (Interface Associates, Laguna Niguel, CA) for measurement of inspiratory and expiratory flows and volumes; calibration was performed with a 3-liter syringe (Hans Rudolph, Kansas City, MO) over a range of different flow profiles. Respired gas, sampled at 1 ml/s from the mouthpiece, was analyzed using a quadrupole mass spectrometer (MSX, Morgan Medical, Kent, UK) for O_2, CO_2, and N_2 concentration; calibration was performed using two precision-analyzed gas mixtures that spanned the inspiratory-expiratory range, and was checked immediately posttest. The time delay between the gas concentration and volume signals was determined automatically using algorithms specified by the manufacturers (MSX, Morgan Medical) and checked periodically against values obtained by passing a bolus of CO_2-rich gas through the system using a low dead space solenoid valve (5). The volume and gas concentration signals were sampled and digitized every 20 ms and time aligned for online breath-by-breath measurement of pulmonary gas exchange variables (5). Heart rate and arterial O_2 saturation were monitored using a short-range telemetry monitor (S610i, Polar Electro Oy, Kempele, Finland) and finger pulse oximetry (Biox 3745, Ohmeda, respectively).

**Protocols**

All exercise tests were conducted from an initial 20-W baseline of at least 4 min, with a final recovery phase also at 20 W for at least 6 min. No subject completed more than one test on a given day, which required a total of 10 (and in some cases 11) separate visits to the laboratory. Subjects participated in no more than three test sessions per week.

**Protocol 1: Maximal incremental ramp test.** Following familiarization, subjects first completed a maximal ramp-incremental test (15 W/min) to the limit of tolerance (Fig. 1A). This allowed determination of VO_2peak, calculated as the average VO_2 for an integral number of breaths over the last ~20 s of the incremental phase and estimation of \( \text{TH}_\text{m} (\text{TH}) \) using the V-slope method (6) and supporting ventilatory and pulmonary gas exchange criteria (59).

**Protocol 2: Determination of the P-t relationship.** Subjects subsequently performed a series of four constant-load tests to the limit of tolerance (Fig. 1B), each at different work rates chosen to induce exhaustion over a range of times (\( t_{\text{lim}} \)) between ~3 and 12 min. CP and W' were estimated as the power intercept and slope, respectively, by linear regression from the power vs. \( t_{\text{lim}} \) relationship (21, 40). In those infrequent instances (\( n = 2 \)) where the four-point P-t relationship was not adequately characterized (defined as the SE of the CP estimation being \( > \pm 3 \text{ W} \)), an additional test was performed at a different work rate to improve the confidence of the estimation. Accurate characterization of the P-t relationship also allowed the work rate that would be expected to induce exhaustion at 8 min (WR_e) to be interpolated; this value was then used as the very-heavy intensity work rate for the priming bout in protocols 3 and 4. WR_e was determined to be suitable for that of the priming bout (i.e., supra-CP).
as preliminary experiments had shown this to be of both a sustainable duration and sufficient work rate so as to result in a significant elevation of blood [L⁻¹] and the near attainment of VO₂max, but without eliciting the limit of tolerance.

Protocol 3: The effects of prior exercise on maximal incremental ramp exercise. Following completion of protocol 2, subjects completed a 6-min constant-load priming bout at WR₈. This was immediately followed by a 2-min 20-W recovery period (intended to be sufficiently short to ensure limited recovery of both VO₂ and blood [L⁻¹]) and then a maximal incremental ramp test (15 W/min) to the limit of tolerance (Fig. 1C).

Protocol 4: The effects of prior exercise on the P-t relationship. Finally, subjects completed a second series of four constant-load exercise tests to the limit of tolerance at work rates consistent with those used in protocol 2, but with each preceded by a 6-min constant-load priming bout at WR₈ followed by a 2-min 20-W recovery period (Fig. 1D).

Blood Sampling

At predetermined points throughout all protocols (Fig. 1, arrows), finger-tip capillary blood samples were taken (~25 μl) and analyzed immediately posttest for [L⁻¹] using an automated analyzer (Analox GM-7, Analox Instruments, London, UK). The analyzer was calibrated before the analysis of each set of blood samples using an 8 mM standard solution, the concentration of which was also checked postanalysis.

Analyses

For each test, the breath-by-breath data were edited to exclude occasional outlying breaths (> ±4 SD of the local mean), which were the result of coughs or swallows, etc (29). For the constant-load tests, baseline VO₂ for the initial 20-W warm-up phase was calculated as the mean VO₂ over the final 60 s. “Baseline” VO₂ following priming exercise was calculated as the mean VO₂ recorded over the last ~20 s prior to the imposition of the subsequent exercise bout. VO₂peak was calculated as the average VO₂ during the last ~20 s (see above) before attaining the limit of tolerance. Comparison of the VO₂peak values from tests at different work rates allowed verification (or not) of VO₂max in each subject.

Subsequently, all breath-by-breath responses were time aligned to exercise onset and interpolated on a second-by-second basis. As each subject completed four to five tests at WR₈ (i.e., protocols 3 and 4), this allowed us to average these to yield an average VO₂ profile for each subject. All data sets (averaged or single) were then time averaged (10 s) and, following deletion of the initial phase 1 component [the phase 1–phase 2 transition being identified as the time at which the respiratory ex-

![Fig. 1. Schematic representation of the work rates (WR) performed during each exercise protocol. A: protocol 1, maximal ramp-incremental test. B: protocol 2, series of 4 constant-load exercise tests, each at a different WR, for determination of the power-duration (P-t) relationship (dotted line). C: protocol 3, priming exercise at the WR expected to induce exhaustion at 8 min (WR₈) followed by a maximal incremental ramp test. D: protocol 4; priming exercise at WR₈ followed by the same series of 4 constant-load exercise tests used in protocol 2, again for determination of the P-t relationship (dotted line). All tests were performed to the limit of tolerance. Arrows represent blood sampling time points. CP, critical power.](http://jap.physiology.org/Downloadedfrom/10.220.33.4/10.220.33.4/10.220.33.4)
change ratio and end-tidal PO2 start to increase systematically, and end-tidal PCO2 starts to decrease, typically 15–20 s after exercise onset (58). Two indices of the \( \dot{V}O_2 \) response were isolated using the method of Rossiter et al. (45):

\[
\dot{V}O_2(t) = \dot{V}O_2(BL) + \Delta \dot{V}O_2(\text{SS}), [1 - e^{-\delta t}]
\]

where \( \dot{V}O_2(BL) \) is the baseline \( \dot{V}O_2 \), \( \Delta \dot{V}O_2(\text{SS}) \) is the projected asymptotic \( \dot{V}O_2 \) increment, and \( \delta \) is a delay term that is similar but not equal to the phase 1–2 transition time (58). Two indices of the \( \dot{V}O_2 \) were estimated: 1) the magnitude of \( \dot{V}O_2 \) increase over a fixed time interval (typically a 1-min interval as many of the tests were rather short) starting from a point just after the emergence of the \( \dot{V}O_2 \) (\( \Delta \dot{V}O_2(\text{SS})/\Delta t \); compare with Ref. 47); and 2) the \( \dot{O}_2 \) cost of the slow component, given by the integral of the difference between the actual \( \dot{V}O_2 \) response profile and the extrapolated fundamental \( \dot{V}O_2 \) asymptotic value over a time interval between the point at which the \( \dot{V}O_2(\text{SS}) \) first became discernible and the end-exercise point. The onset of the \( \dot{V}O_2(\text{SS}) \) was estimated as the time at which the residuals of the phase 2 model fit first systematically departed from zero (45).

The significance of the effects of supra-CP priming exercise on parameters of postpreroxid exercise performance was established using a Student’s paired \( t \)-test or an ANOVA, as appropriate, with differences considered significant if \( P < 0.05 \). All values are quoted as means ± SD unless otherwise stated.

### RESULTS

#### Protocol 1: Maximal Incremental Ramp Exercise

Following the initial kinetic phase, \( \dot{V}O_2 \) increased as a linear function of work rate (e.g., Fig. 2, open symbols) with a functional gain (\( \Delta \dot{V}O_2/\Delta \text{WR} \)) of 11.1 ± 0.4 ml·min\(^{-1} \cdot \text{W}^{-1} \), attaining \( \dot{V}O_2 \) at 3.99 ± 0.46 l/min (Table 1). \( \hat{\dot{L}} \) occurred at 1.83 ± 0.31 l/min, which was equivalent to 46% of \( \dot{V}O_2 \) on average (Table 1). Arterialized capillary [L–] at the limit of tolerance averaged 8.9 ± 1.7 mM, i.e., an increment (\( \Delta [\text{L–}] \)) of 8.1 ± 1.7 mM above the pre-exercise (20 W) baseline (Table 1).

#### Protocol 2: Determination of the P–t Relationship

For each subject, \( \text{t}_\text{lim} \) for the very-heavy intensity constant-load exercise tests was inversely correlated with power, and the data were well fit to a linear regression of power vs. \( \text{t}_\text{lim} \) (Fig. 3A, open symbols). This goodness-of-fit for all linear regressions was confirmed by \( r^2 \)-values >0.98, and the SE of the CP estimation in all subjects lying within ±3 W. CP and W’ were estimated to be 242 ± 36 W and 16.13 ± 2.33 kJ or 205 ± 31 J/kg, respectively (Table 2), consistent with earlier reported values for young physically active men (e.g., 13, 21, 40). Although this is the conventional method utilized to estimate CP and W’ (e.g., 21, 40), this regression technique assigns all “error” to the \( y \)-, or power-, axis. Hence, CP and W’ were re-estimated with the independent power variable being assigned to the \( x \)-axis and 1/\( \text{t}_\text{lim} \) to the \( y \)-axis (e.g., 13; Fig. 3B, open symbols). The CP and W’ estimates were, however, unaffected (averaging 242 ± 36 W and 16.43 ± 2.10 kJ, respectively; \( P > 0.05 \)).

In all subjects, the [L–] and \( \Delta [\text{L–}] \) values at end-exercise were independent of work rate and averaged 9.4 ± 1.2 and 8.4 ± 1.1 mM, respectively (Table 2); these were not significantly different from the corresponding values at the limit of tolerance on the ramp test. In all subjects, end-exercise \( \dot{V}O_2 \) met the criterion for \( \dot{V}O_2 \text{max} \) by being independent of work rate (Fig. 4, open symbols), and averaged 3.93 ± 0.38 l/min (Table 2), which was not significantly different from the corresponding \( \dot{V}O_2 \) obtained on the ramp test (Table 1).

The initial phase of the \( \dot{V}O_2 \) response was typically well fit to the single monoexponential model, with a delayed \( \dot{V}O_2 \) first becoming discernible (e.g., Fig. 4, open symbols). As there were no obvious WR-related trends in any of the kinetic indices, the individual values from each of the four constant-load tests performed by each subject were averaged (Table 2). For the group as a whole, the fundamental \( \tau \) averaged 28.3 ± 5.4 s, the rate of \( \dot{V}O_2 \) development (\( \Delta \dot{V}O_2/\tau \)) averaged 0.178 ± 0.047 kJ.s \( ^{-1} \).
1·min⁻¹·min⁻¹, and the O₂ cost of the VO₂SC averaged 2.63 ± 0.75 liters (Table 2).

**Protocol 3: Effects of Prior Exercise on Maximal Incremental Ramp Exercise**

The very-heavy intensity priming work rate (WR₈) averaged 275 ± 34 W (Table 3). At the termination of WR₈ (i.e., at 6 min; Fig. 1C), [L⁻] and Δ[L⁻] averaged 8.2 ± 1.2 and 7.1 ± 1.1 mM, respectively. VO₂ attained an average value of 3.86 ± 0.43 l/min, which was equivalent to 98 ± 0.4% of VO₂max. The fundamental τ, estimated from the average of four to five “like” priming bouts transitions for each subject, averaged 24.5 ± 4.3 s, which was not significantly different from that for the prepriming constant-load tests conducted in protocol 2.

During the 2 min of 20-W exercise between the two high-intensity bouts, VO₂ partially recovered (Fig. 1C; Fig. 2, filled symbols) to reach an average value of 1.23 ± 0.12 l/min, which corresponded to an elevation of ~480 ml/min above the initial 20-W baseline value. In all cases, this was appreciably below the VO₂ value at τ₀ on the control ramp tests (Table 1). Blood [L⁻] continued to rise throughout the 20-W recovery period to attain an average value of 8.6 ± 1.4 mM immediately prior to the onset of subsequent exercise.

Despite the subsequent ramp test being initiated against a higher baseline VO₂ (Fig. 2, filled symbols), neither ramp duration nor peak work rate for the postpriming ramp test differed from the corresponding values on the initial prepriming ramp test: i.e., 1.162 ± 164 vs. 1.191 ± 135 s (post- vs. prepriming; P > 0.05) and 310 ± 40 vs. 318 ± 34 W (P > 0.05), respectively (Tables 1 and 3). During the ramp phase, VO₂ again increased as a linear function of work rate following a more-complex kinetic phase, occasioned by the continuing recovery during the early incremental phase (Fig. 2, filled symbols). The functional gain and VO₂max were not significantly different compared with prepriming values (ΔVO₂/ΔWR: 10.7 ± 0.3 ml·min⁻¹·W⁻¹; VO₂max: 3.97 ± 0.46 l/min; Fig. 5A, open symbols; Tables 1 and 3). However, τ₀ could not be validly discerned, because of the presence of a “pseudo-threshold” arising, presumably, from the influence of the residual lactic acidosis from the priming exercise on CO₂ stores dynamics (57). Blood [L⁻] obtained at the limit of tolerance averaged 9.6 ± 1.7 mM (Table 3), which was not significantly different from the corresponding values for the initial incremental test (Fig. 5B, open symbols; Tables 1 and 3), representing a Δ[L⁻] of 1.0 ± 1.4 mM from the elevated prereg “baseline” value (Table 3).

**Protocol 4: Effects of Prior Exercise on the P-t Relationship**

Following the priming exercise at WR₈ (Fig. 1D), tlim for very-heavy intensity constant-load exercise was significantly reduced (Fig. 5E) but remained closely and hyperbolically correlated with power (Fig. 3, filled symbols); again with Δ > 0.98 in all cases. CP averaged 241 ± 39 W, which was not significantly different from the corresponding prepriming values (protocol 2; 242 ± 36 W; Fig. 5C; Tables 2 and 4). However, W’ was significantly reduced postpriming, averaging 10.61 ± 2.07 kJ (Figs. 3 and 5D; Tables 2 and 4); i.e., a 34.2 ± 9.1% reduction relative to the prepriming value. The postpriming reductions in W’ and tolerable duration were well correlated (Fig. 5F); on average, a ~35% reduction in W’ was associated with a ~35% reduction in tlim.

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**Table 2. Prepriming constant-load test responses (protocol 2)**

<table>
<thead>
<tr>
<th>Subject</th>
<th>CP, W</th>
<th>W’, kJ</th>
<th>Baseline, [L⁻], mM</th>
<th>End-ex, [L⁻], mM</th>
<th>Baseline VO₂, l/min</th>
<th>VO₂max, l/min</th>
<th>tVO₂, s</th>
<th>VO₂scO₂ Cost, liter</th>
<th>VO₂scΔVO₂/Δt, 1·min⁻¹·l·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>199</td>
<td>15.68</td>
<td>1.03</td>
<td>10.6</td>
<td>0.72</td>
<td>3.41</td>
<td>28.1</td>
<td>2.55</td>
<td>0.130</td>
</tr>
<tr>
<td>2</td>
<td>266</td>
<td>15.67</td>
<td>0.95</td>
<td>9.0</td>
<td>0.83</td>
<td>4.25</td>
<td>21.2</td>
<td>3.25</td>
<td>0.214</td>
</tr>
<tr>
<td>3</td>
<td>213</td>
<td>15.25</td>
<td>0.81</td>
<td>7.9</td>
<td>0.72</td>
<td>3.60</td>
<td>34.2</td>
<td>1.47</td>
<td>0.151</td>
</tr>
<tr>
<td>4</td>
<td>297</td>
<td>13.69</td>
<td>0.75</td>
<td>8.5</td>
<td>0.70</td>
<td>4.41</td>
<td>26.7</td>
<td>2.89</td>
<td>0.140</td>
</tr>
<tr>
<td>5</td>
<td>240</td>
<td>15.88</td>
<td>1.10</td>
<td>9.2</td>
<td>0.70</td>
<td>4.07</td>
<td>35.0</td>
<td>3.48</td>
<td>0.250</td>
</tr>
<tr>
<td>6</td>
<td>236</td>
<td>20.60</td>
<td>1.11</td>
<td>11.0</td>
<td>0.74</td>
<td>3.85</td>
<td>24.5</td>
<td>2.12</td>
<td>0.182</td>
</tr>
<tr>
<td>Mean</td>
<td>242</td>
<td>16.13</td>
<td>0.96</td>
<td>9.4</td>
<td>0.74</td>
<td>3.93</td>
<td>28.3</td>
<td>2.63</td>
<td>0.178</td>
</tr>
<tr>
<td>SD</td>
<td>36</td>
<td>2.33</td>
<td>0.15</td>
<td>1.2</td>
<td>0.05</td>
<td>0.38</td>
<td>5.4</td>
<td>0.75</td>
<td>0.047</td>
</tr>
</tbody>
</table>

W’, curvature constant; VO₂sc, VO₂ slow component.
Fig. 4. The VO\textsubscript{2} responses pre- (open) and post-priming (filled) during 4 different constant-load WRs in a representative subject (subject 1), with the fundamental best-fit exponential superimposed. Note that, for the same work rate, there was a significant reduction in tolerable duration following priming exercise.

Postpriming, VO\textsubscript{2max} was unchanged (3.97 ± 0.34 l/min; Fig. 5A, filled symbols; Tables 2 and 4). Also, end-exercise [L\textsuperscript{-}] averaged 9.9 ± 1.5 mM (Table 4), which was not significantly different from prepriming values (Fig. 5B, filled symbols; Table 2); however, this yielded a considerably smaller Δ[L\textsuperscript{-}] of only 1.4 ± 0.8 mM, because of the elevated postpriming 20-W baseline value (8.6 ± 1.4 mM).

The fundamental \( \tau \) averaged 25.6 ± 3.5 s (Table 4; Fig. 4, filled symbols), which was not significantly different from that for the prepriming constant-load tests (Table 2; Fig. 4, open symbols) or for the priming bout (see above). The absolute asymptotic fundamental VO\textsubscript{2} value at any given work rate was significantly greater postpriming, reflective of the elevated VO\textsubscript{2} baseline with little effect on the fundamental ΔVO\textsubscript{2}, but with no clear tendency for this increase to become more prominent with increasing work rate (e.g., Fig. 4). Also, the VO\textsubscript{2sc} at a given work rate was less prominent postpriming (Fig. 4), as evidenced by both a lower average O\textsubscript{2} cost of 0.65 ± 0.31 vs. 2.63 ± 0.75 liters (\( P < 0.05 \)) and also by a slower average rate of development (ΔVO\textsubscript{2}/Δt) of 0.075 ± 0.054 vs. 0.178 ± 0.047 l/min\textsuperscript{-1}·min\textsuperscript{-1} (\( P < 0.05; \) Tables 2 and 4). In two instances, however, no VO\textsubscript{2sc} could be discerned (compare with Ref. 45), despite \( t_{lim} \) being appreciably longer than 3 min [i.e., in excess of the latency reported for VO\textsubscript{2sc} (reviewed in 55)]. In two further instances, when \( t_{lim} \) was achieved in less than ~3 min, a VO\textsubscript{2sc} was also not discernible.

**DISCUSSION**

The novel findings of this investigation are that following very-heavy intensity priming exercise (i.e., above CP) of a duration sufficient to induce a substantial end-exercise elevation of blood [L\textsuperscript{-}], which is essentially maintained over the abbreviated (2 min) intervening recovery phase, as follows.

First, the P-t relationship for subsequent supra-CP exercise remained well described by a hyperbolic function (Fig. 3); second, there was no significant change in CP, VO\textsubscript{2} functional gain, VO\textsubscript{2max}, or blood [L\textsuperscript{-}] at the limit of tolerance (Tables 1–4; Figs. 2–5); and third, \( W^* \), and \( t_{lim} \) were significantly reduced (Tables 2 and 4; Figs. 3 and 4), in close proportion (Fig. 5).

**Priming exercise intensity.** Our demonstration of a reduced supra-CP exercise tolerance following supra-CP priming does not, at first sight, appear readily reconcilable with earlier “priming” studies (11, 12, 25, 27; see INTRODUCTION). However, it should be emphasized that the majority of these studies did not formally distinguish between “heavy” and “very-heavy” intensity domains (55) when assigning priming and postpriming work rates. Neither has there been a strict standardization of the intervening recovery period with regard to duration, intensity, or format (rest, mild exercise, or some combination of both being variously used). Despite this, there is an emerging consensus (e.g., 4, 9–11, 15, 28, 31, 38, 50, 53; see INTRODUCTION), supported by the results of the present investigation, of an overall speeding of the VO\textsubscript{2} response that reflects an increase in the fundamental asymptote (e.g., Fig. 4; Tables 2 and 4) and a less prominent VO\textsubscript{2sc} (e.g., Fig. 4; Tables 2 and 4) that serves to modulate VO\textsubscript{2} kinetics toward a first-order characterization (e.g., 45), but with no change in the fundamental \( \tau \), at least for cycle ergometry (see INTRODUCTION; e.g., Fig. 4; Tables 2 and 4).

### Table 3. Postpriming maximal incremental ramp test responses (protocol 3)

<table>
<thead>
<tr>
<th>Subject</th>
<th>WR(_{W_1}), W</th>
<th>WR(_{Peak}), W</th>
<th>Duration, s</th>
<th>VO\textsubscript{2max}, l/min</th>
<th>ΔVO\textsubscript{2}/ΔWR, ml·min\textsuperscript{-1}·W\textsuperscript{-1}</th>
<th>( \dot{V}\textsuperscript{O}_{\text{L}}, l/min )</th>
<th>( \ddot{V}\textsuperscript{O}<em>{\text{L}}, %\text{VO}</em>{\text{2max}} )</th>
<th>End-ex [L\textsuperscript{-}], mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>232</td>
<td>280</td>
<td>1,037</td>
<td>3.48</td>
<td>10.5</td>
<td>—</td>
<td>—</td>
<td>10.8</td>
</tr>
<tr>
<td>2</td>
<td>298</td>
<td>315</td>
<td>1,185</td>
<td>4.20</td>
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<td>245</td>
<td>274</td>
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<td>384</td>
<td>1,462</td>
<td>4.72</td>
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<td>273</td>
<td>290</td>
<td>1,081</td>
<td>3.92</td>
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<td>279</td>
<td>317</td>
<td>1,189</td>
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<td>—</td>
<td>—</td>
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<tr>
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<td>310</td>
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<td>—</td>
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<tr>
<td>SD</td>
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<td>40</td>
<td>164</td>
<td>0.46</td>
<td>0.3</td>
<td>—</td>
<td>—</td>
<td>1.7</td>
</tr>
</tbody>
</table>
This suggests a reduced reliance on “fatigue-inducing” anaerobic mechanisms of energy provision (and, by inference, a reduction in the $O_2$ deficit; e.g., 2, 18, 26, 45) and, as first posited by Gerbino et al. (18), a consequential increase in the tolerable duration of supra-CP work rates. Indeed, Jones et al. (25) and Burnley et al. (11) both reported an increased exercise tolerance subsequent to priming: the former as an increased exercise time at a fixed power output (with a “tendency” toward an increase in $W'$), and the latter as an increased “maximized” power output for a fixed duration. However, the priming exercise used in these studies was of heavy rather than very-heavy intensity [i.e., 50% of “delta,” which, at least in the study of Jones et al. (25), was below CP], and therefore unlikely to appreciably compromise $W'$ (compare with 13, 16); there being only a slight (although significant) elevation of the postpriming baseline blood [L$^-$.]. In contrast, Koppo and Bouckaert (27) found that priming cycle ergometer exercise at 90% V$\dot{O}_2$peak (likely to be supra-CP given the significant elevation in the postpriming baseline blood [L$^-$.]) for 6 min had no effect on tlim at 95% of V$\dot{O}_2$peak, despite a significant reduction in the magnitude of V$\dot{O}_2$SC how $W'$ might have been affected can only be speculated on; however, as the P-t relationship was not defined in this study. Finally, the study of Carter et al. (12) is not readily comparable as the postpriming exercise was a single work rate selected to coincide with CP.

Our observations of a consistently reduced exercise tolerance postpriming extends the early demonstration by Karlsson...
et al. (26) that prior cycle ergometer or arm-cranking exercise at work rates designed to elicit fatigue within ~5 min (and therefore presumably above CP) resulted in a reduced tolerable duration of subsequent exercise with the other modality; effects that were ascribed (in the first instance) to the intramuscular accumulation of L− and/or H+ over the priming bout. Furthermore, two subjects in the study of Gerbino et al. (18) clearly evidenced a reduced exercise tolerance postpriming as they were unable to complete the designated 6-min duration of the postpriming bout (this fixed-duration paradigm did not allow this to be assessed in the remaining subjects, however). And more recently, Wilkerson et al. (60) reported a reduced tolerable duration of high-intensity cycle ergometer exercise (likely of severe intensity, as it could be tolerated for only 2–3 min and there being no discernible VO2peak) following multiple-sprint “all-out” priming exercise. Although it is unclear to what extent this sprint priming paradigm is comparable to the more conventional sustained supra-CP paradigm used in the present study with regards to the degree of W′ depletion, Wilkerson et al. (60) did report an appreciably elevated VO2 and blood [L−] immediately prior to the postpriming bout, the magnitude of the latter averaging only slightly less than that we observed, i.e., 7.7 ± 0.9 compared with our value of 8.6 ± 1.4 mM (Table 4). Their results show an interesting departure from those of the present study, however, VO2peak was not attained at end exercise on either the unprimed bout (averaging 88% of VO2peak) or the primed bout (averaging 94% of VO2peak; Ref. 60). The reasons for this are unclear.

Thus a key determinant of whether sustained supra-θh, priming exercise induces a performance improvement for subsequent supra-CP exercise appears to be the intensity of the priming bout (i.e., whether this is below or above CP) and the nature of the intervening recovery period. These are likely important as both will dictate the extent to which blood (and presumably muscle) lactate levels remain elevated at the commencement of the postpriming bout.

Consistent with this suggestion, Burnley et al. (11) recently proposed that post-priming “baseline” blood [L−] values <5 mM are associated with an increase in performance (i.e., 11, 25), while values modestly >5 mM are associated with no discernible change (i.e., 11, 27) and those substantially >5 mM would lead to a reduction in performance (i.e., 18, 26, 60; and the present study, Figs. 3 and 5). It is tempting here to draw an association with the maximum lactate steady state (MLSS), which, on average, is in the region of 5 mM and which has been argued to correspond to CP (see INTRODUCTION). In other words, therefore, priming strategies that are sub-CP are predicted to confer a performance advantage, while those that are clearly above CP are not. Caution should be exercised, however, the bioenergetic conditions prevailing in association with MLSS (i.e., quasi steady-state sustained unprimed exercise) are unlikely to be closely comparable to those of the highly non-steady-state conditions prevailing during the initial stages of recovery from supra-CP exercise, not the least that blood [L−] is not stable and that the dynamics of lactate processing (e.g., intra-myocyte, cell-to-cell shuttling, cell-capillary transport; e.g., 8, 19, 30), are likely to be rather complex. More importantly, given the likely complexity of the determinants of W′, a predictor of performance based simply on the profile of blood [L−] is overly simplistic, as is illustrated by our demonstration that the tolerable duration of supra-CP exercise is highly dependent on the preperformance W′ value (Fig. 5F) but not simply on preexercise blood [L−].

Mechanisms of reduced exercise tolerance. The demonstration that key aerobic demarcators of exercise intensity (55) remain unchanged following supra-CP priming exercise suggests that the sustainability of exercise in the heavy-intensity domain should be essentially unaffected by supra-CP priming, while the impairment of exercise tolerance above CP is dictated by the extent of W′ repletion. However, we had no way of directly assessing W′ at this time point. Rather, we assumed that the estimate of W′ extracted from the postpriming P-t relationship was equal to, or closely reflective of, the value that had prevailed at the end of the 2-min 20-W recovery period; i.e., that there was no “repletion” of W′ during the postpriming supra-CP exercise. And while we cannot rule out that some repletion might have continued into the postpriming exercise period itself, perhaps in muscle fibers with a high perfusion-to-metabolic rate ratio, the inference that W′ cannot be replenished during exercise in the very-heavy intensity domain would suggest that such an effect is unlikely to be significant (i.e., the “flux” of W′ during supra-CP exercise is unidirectional; Ref. 13). We suggest that the reason that performance on the ramp test was unaffected by the supra-CP priming (in contrast to the supra-CP constant-load exercise) is probably because the ramp test has far less reliance on anaerobiosis (with its consequent sequellae); that is only approximately half the tolerable work rate range was above θh, in addition supra-CP work rates were not achieved until ~15 min after priming and, furthermore, there was no evidence of VO2recruitment (the VO2-WR relationship remaining linear throughout).

The extent to which the priming exercise “depleted” W′ is likewise uncertain, as the exercise was not performed to the limit of tolerance (i.e., lasting 6 min, compared with the predicted tlim of 8 min); although end-exercise VO2 was close to maximum (i.e., 98%, on average). While intramuscular

Table 4. Postpriming constant-load test responses (protocol 4)

<table>
<thead>
<tr>
<th>Subject</th>
<th>CP, W</th>
<th>W′, kJ</th>
<th>Baseline [L−], mM</th>
<th>End-ex [L−], mM</th>
<th>Baseline VO2, l/min</th>
<th>VO2peak, l/min</th>
<th>tVO2, s</th>
<th>VO2rec Cost, liter</th>
<th>VO2recΔVO2Δt, l/min−1•min−1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>195</td>
<td>12.60</td>
<td>8.5</td>
<td>11.2</td>
<td>1.12</td>
<td>3.51</td>
<td>30.5</td>
<td>0.81</td>
<td>0.048</td>
</tr>
<tr>
<td>2</td>
<td>266</td>
<td>9.79</td>
<td>8.5</td>
<td>9.4</td>
<td>1.31</td>
<td>4.30</td>
<td>28.9</td>
<td>0.17</td>
<td>0.055</td>
</tr>
<tr>
<td>3</td>
<td>214</td>
<td>10.53</td>
<td>7.2</td>
<td>8.6</td>
<td>1.17</td>
<td>3.69</td>
<td>22.1</td>
<td>0.58</td>
<td>0.174</td>
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<tr>
<td>4</td>
<td>303</td>
<td>8.90</td>
<td>6.9</td>
<td>8.1</td>
<td>1.11</td>
<td>4.39</td>
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<td>0.99</td>
<td>0.063</td>
</tr>
<tr>
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<td>239</td>
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<td>9.7</td>
<td>10.1</td>
<td>1.28</td>
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<td>0.90</td>
<td>0.093</td>
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<tr>
<td>6</td>
<td>231</td>
<td>13.52</td>
<td>10.5</td>
<td>12.1</td>
<td>1.41</td>
<td>3.90</td>
<td>26.0</td>
<td>0.43</td>
<td>0.018</td>
</tr>
<tr>
<td>Mean</td>
<td>241</td>
<td>10.61</td>
<td>8.6*</td>
<td>9.9</td>
<td>1.23*</td>
<td>3.97</td>
<td>25.6</td>
<td>0.65*</td>
<td>0.075*</td>
</tr>
<tr>
<td>SD</td>
<td>39</td>
<td>2.07</td>
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<td>1.5</td>
<td>0.12</td>
<td>0.34</td>
<td>3.5</td>
<td>0.31</td>
<td>0.054</td>
</tr>
</tbody>
</table>

*Significant (P < 0.05) difference in the pre vs. postpriming value.
[ATP] has been reported to be unchanged for very-heavy intensity constant-load exercise (43, 46), other putative “storage” elements will presumably have been diminished. For example, the dominant fundamental component of PCr hydrolysis would be predicted to effectively have stabilized within about four time-constants of the response (i.e., a first-order response; Ref. 46). In our study, taking the 24.5-s value for the fundamental $\tau_{\mathrm{Vo}_2}$ as a proxy, this would require some 100 s with the CP slow component providing an additional smaller contribution up to the 6-min point (46). Likewise, given the appreciable elevation of blood $[L^{-}]$ at the end of the priming bout (i.e., 8.6 $\pm$ 1.4 mM, which approached maximum values; Tables 1–4), anaerobic breakdown of muscle glycogen stores will also have occurred. However, it seems unlikely that any such decrement in muscle [glycogen] would be of performance-limiting dimensions, given the relatively short duration of priming phase (e.g., 49), although the possibility of regional foci of depletion cannot be ruled out (e.g., 52). During the course of very-heavy constant-load exercise, there is also evidence of appreciable intramuscular accumulation of putative “fatigue-related” metabolites, such as $H^{+}$ and inorganic phosphate (43, 46). We can only speculate on the extent to which intramuscular stores depletion and/or metabolite accumulation contributed to the subsequent repletion of $W$’, albeit incomplete, over the postpriming recovery period. For example, neither $\mathrm{Vo}_2$ [and presumably intramuscular [PCr] (46)] nor blood $[L^{-}]$ even approached control baseline levels (Tables 2 and 4).

What was consistently the case, however, was the lack of effect of the priming intervention on $\mathrm{Vo}_{2\max}$ (Fig. 5) and CP (Figs. 2 and 5), despite $\mathrm{Vo}_2$ attaining near-maximal values on the priming bout (i.e., $\sim 98\% \, \mathrm{Vo}_{2\max}$). This observation coheres with the earlier demonstrations of the insensitivity of CP to interventions such as creatine supplementation (33, 51) and glycogen depletion (34), while being increased by hyperoxia and decreased by hypoxia (35, 56) and being increased by endurance training (e.g., 41). Our results are at odds with the earlier suggestion of Coats et al. (13) that CP might actually be reduced by supra-CP priming. These authors suggested that the premature fatigue seen in some of their subjects may have resulted from a reduced CP value consequent to the priming exercise. The cause of this early “fatigue” in these previous investigations is unclear, however, but the present study suggests that this was unlikely to have resulted from prior exercise affecting CP. Other possible explanations may include variations in factors such as the kinetics of intra- and extramyocyte $H^{+}$ and $L^{-}$ handling (e.g., 8, 19, 30), regional substrate depletion (e.g., PCr, glycogen), muscle-fiber recruitment profiles, and/or central neural processes related, for example, to inappropriate levels of central neurotransmitters (dopamine, serotonin; e.g., 32, 36, 37).

What we cannot answer unequivocally is whether $\theta_{\mathrm{L}}$ was affected by prior supra-CP exercise, owing to the presence of a pseudo-threshold (57) during the postpriming ramp-incremental test. However, the lack of effect on $\mathrm{Vo}_{2\max}$ and CP would suggest not, as would the demonstrations that, following high-intensity priming, $\mathrm{Vo}_2$ kinetics remain well described as monoeXponential for work rates that were within $\sim 80–90\%$ of $\theta_{\mathrm{L}}$ under control conditions (e.g., 18).

The lack of effect of the supra-CP priming on the fundamental $\tau_{\mathrm{Vo}_2}$ (Tables 2 and 4) is consistent with earlier studies (e.g., 4, 9–11, 15, 28, 31, 38, 48, 50). This suggests that putative intramuscular rate-limiting processes controlling mitochondrial $O_2$ utilization for which [PCr] serves as a kinetic proxy (46), would be essentially unaffected by the prior supra-CP priming exercise.

The elevated absolute fundamental $\mathrm{Vo}_2$ asymptotic value (Fig. 4) is also consistent with earlier studies (e.g., 4, 9–11, 15, 28, 31, 38, 48, 50). In our study, this was essentially the consequence of the elevated baseline $\mathrm{Vo}_2$ at the end of the 2-min recovery period (Fig. 4), as the absolute fundamental $\mathrm{Vo}_2$ asymptotic value was elevated by a similar amount (see also Refs. 10, 28, 31, 38, 50). And when sufficient time is allowed for the full recovery of $\mathrm{Vo}_2$ back to control baseline levels, there is therefore an increase in the fundamental gain (4, 9–11, 15).

The reasons for this increased fundamental $\mathrm{Vo}_2$ asymptotic value are not at all clear, although the prevailing evidence (in humans, at least) does not support a significant role for an increased muscle $O_2$ delivery consequent to improved perfusion, given the insensitivity of the fundamental $\tau$ to high-intensity priming, at least for cycle ergometry (see above). An involvement of putative intramuscular enzymatic controllers such as pyruvate dehydrogenase also seems unlikely, given the demonstration that dichloroacetate administration actually reduces the fundamental $\mathrm{Vo}_2$ and [PCr] amplitudes for high-intensity exercise (44). Some authors have advocated a role for the recruitment of additional glycolytic muscle fibers with low oxidative capacity early in the postpriming exercise, consequent to fatigue-related influences on sarcolemmal excitation thresholds imposed by the priming bout (4, 9, 10, 48). However, experimental support for this proposal in humans is limited to surface electromyography (9; but compare with Refs. 50, 53), which may not have sufficient sensitivity to uniquely resolve fiber type recruitment patterns. Nonetheless, such a mechanism seems to imply that shorter recovery periods of the kind used in the present study should amplify this effect; i.e., eliciting recruitment of a greater number of muscle fibers and therefore a more marked elevation of the fundamental $\mathrm{Vo}_2$ asymptotic value. Possibly arguing against an appreciable alteration in the motor unit recruitment profile, however, is our observation that, on the postpriming ramp test, $\mathrm{Vo}_2$ increased linearly with respect to work rate over all but the initial kinetic portion of the ramp phase (Fig. 2) with an unchanged functional gain relative to the control ramp test (Tables 1 and 3); i.e., there was no evidence of an increased gain in any of our subjects.

Importantly, the consequence of the elevated fundamental $\mathrm{Vo}_2$ asymptote is that, despite a slower development of the $\mathrm{Vo}_{2\max}$, the available $\mathrm{Vo}_2$ range within which the $\mathrm{Vo}_{2\max}$ could express itself was smaller; i.e., $\mathrm{Vo}_{2\max}$ was attained at end exercise (Fig. 4) and was unchanged by the priming (Fig. 5). Hence, exercise tolerance was reduced.

The implications of these observations for postpriming $W'$ utilization can only be conjectural, however. The retained hyperbolic $P_{\text{lim}}$ characteristic is consistent with its underlying determinants collectively continuing to change either linearly or exponentially with time toward some limiting value, at a rate proportional to work rate and therefore the rate of $W'$ utilization (40), but with a reduction in the limiting value and/or an increase the rate at which it is approached. With regard to the latter scenario, for example, the demonstration of an increased...
fundamental VO₂ asymptote suggests a reduction in work efficiency (whose origin remains uncertain; see above), which would be expected to require a greater degree of PCr breakdown and therefore exacerbate depletion of a previously incompletely replenished intramuscular PCr store (48). On the other hand, the degree of exercise-induced metabolic-acidemic stress in both blood (17, 18) and muscle (42, 48) has been shown to be reduced. An alternative scenario that is consistent with the P-tim relationship remaining well described by a hyperbola is that, for any supra-CP work rate, VO₂max is reached prior to complete W’ depletion, but when a constant percentage of the fully depleted W’ is reached; i.e., the remaining portion being functionally inaccessible. However, while the present study does not allow resolution of what the components of W’ actually are, it does demonstrate that W’ “depletion” seems to “shape” the tolerance to very-heavy intensity exercise.

ACKNOWLEDGMENTS

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