Title: Prior upper body exercise reduces cycling work capacity but not critical power

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Abstract

Purpose: This study examined whether metabolite accumulation, induced by prior upper body exercise, affected the power-duration relationship for leg cycle ergometry. **Methods:** Seven males performed, to the limit of tolerance and both without (L) and with (AL) prior severe-intensity arm-cranking exercise, an incremental cycling test and four constant power cycling tests to determine the parameters of the power-duration relationship: critical power (CP) and W'. **Results:** At the onset of cycling exercise plasma lactate (L vs. AL: 1.2 ± 0.1 vs. 11.6 ± 2.9 mEq·L^{-1}) and hydrogen ion (40.4 ± 1.3 vs. 53.1 ± 4.3 nEq·L^{-1}) concentrations were higher during AL compared to L, whereas the strong ion difference (37.8 ± 1.8 vs. 32.4 ± 2.0 mEq·L^{-1}) and bicarbonate concentration (25.7 ± 0.7 vs. 18.3 ± 1.9 mEq·L^{-1}) were lower during AL compared to L (P < 0.01). During incremental exercise maximum cycling power (358 ± 15 vs. 332 ± 21 W) and peak oxygen uptake ($\dot{V}O_2$ peak) (4.31 ± 0.36 vs. 3.71 ± 0.44 L·min^{-1}) were lower during AL compared to L (P < 0.05). The rate of increase in plasma potassium concentration during constant power cycling was greater during AL compared to L (0.09 ± 0.08 vs. 0.14 ± 0.13 mEq·L^{-1}·min^{-1}) (P < 0.05) and exercise duration was 35 ± 15% shorter (P < 0.01). CP was not different between L and AL (267 ± 19 vs. 264 ± 20 W), whereas W' was lower in AL (17.3 ± 5.7 vs. 11.8 ± 4.2 kJ) (P < 0.01). **Conclusion:** The reduced W' following prior upper body exercise indicates that the magnitude of W' is partly dependent on metabolite accumulation.

Key words: Power-duration relationship; metabolites; arm-cranking; cycling

Introduction

Paragraph Number 1 The duration for which severe-intensity constant power exercise can be tolerated increases as a hyperbolic function of decreasing power (19, 22). This power-duration relationship is characterized by two parameters: a power asymptote termed critical power (CP) and a curvature constant termed W'. The CP represents the lower boundary of the severe-intensity exercise domain (23, 28) and, thus, the power that evokes the highest sustainable rate of oxidative metabolism. Exercise above CP is thus characterized by an inexorable accumulation of fatigue-related metabolites (e.g. La^-, H^+, and inorganic phosphate), a continual decline in intramuscular phosphocreatine concentration, and an increasing pulmonary oxygen uptake ($\dot{V}O_2$) towards $\dot{V}O_2max$ (22, 23, 28, 33).

Paragraph Number 2 The W' reflects the maximum amount of work that can be performed above CP irrespective of the rate of W' utilization (17). Once W' is expended exhaustion will ensue unless exercise intensity is reduced below CP to allow restoration of W' (10, 11). However, compared to CP the mechanistic bases of W' are less well defined. The W' is commonly described as a finite energy store determined by oxygen bound to myoglobin, intramuscular phosphocreatine and glycogen (22, 25, 31). In support, and in the absence of any change in CP, oral creatine supplementation increases W' (31), whereas glycogen depletion decreases W' (25). Partial depletion of intramuscular phosphocreatine may also explain, in part, why prior exercise at powers above CP reduces W' (13, 14, 27, 34). However, additional mechanisms are likely to exist since the recovery kinetics of $\dot{V}O_2$ (a proxy for intramuscular phosphocreatine recovery) are faster than the recovery kinetics of W' (13). There is growing support for the notion that W' may thus also depend on the accumulation of fatigue-related metabolites to a critical tolerable limit, which occurs in proportion to the rate of W' utilization (13, 14, 21, 22, 33). The reduction in W' due to prior exercise is therefore difficult to interpret because all exercise was performed using the same

muscle groups and thus energy store depletion presumably coincided with metabolite accumulation.

Paragraph Number 3 The influence of metabolite accumulation on exercise tolerance and W' may be examined more discretely by performing upper body exercise before the criterion bout of leg cycle exercise (3, 24, 26). Severe-intensity upper body exercise elevates blood and muscle [La^-] and [H^+] without affecting leg muscle concentrations of ATP, phosphocreatine, and glycogen (2, 3). Furthermore, during subsequent leg exercise K^+ efflux from the active leg muscle, and increases in interstitial [K^+], are accelerated and exercise tolerance is reduced (3, 26). Prior upper body exercise thus allows the effects of metabolite accumulation on W' to be examined without the confounding, concomitant influence of intramuscular energy store depletion.

Paragraph Number 4 Therefore, the aim of this study was to investigate the effects of metabolite accumulation, induced by prior severe-intensity upper-body exercise, on parameters of the power-duration relationship for leg cycle ergometry. We hypothesized that prior upper body exercise would reduce W' without affecting CP.

Methods

Participants

Paragraph Number 5 Seven healthy, non-smoking, moderately trained males (age: 26 ± 4 years; height: 182 ± 4 cm; body mass: 83 ± 4 kg) provided written informed consent to participate in the study. Participants refrained from caffeine on test days and alcohol and strenuous exercise the day preceding and day of a test. Participants reported to the laboratory at least 2 h post-prandial. The study was approved by the Nottingham Trent University Human Ethics Committee, and all procedures were conducted in accordance with the Declaration of Helsinki.

Experimental design

Paragraph Number 6 Participants attended the laboratory on ten separate occasions, at a similar time of day, separated by at least 48 h. The initial five visits comprised a maximal incremental cycling test and four constant power cycling tests for determination of the power-duration relationship. All cycling tests were performed to the limit of tolerance. The cycling tests were then repeated, in randomized order, during the subsequent five laboratory visits, with each test preceded by severe-intensity intermittent arm-cranking exercise. Hereafter, incremental and constant power cycling tests performed without and with prior arm-cranking exercise are referred to as L_{INC} and AL_{INC}, and L_{CONST} and AL_{CONST}, respectively. Cycling tests during L_{INC} and L_{CONST} trials were preceded by a 20.5 min rest period, which matched the experimental protocol duration preceding the onset of cycling exercise in AL_{INC} and AL_{CONST}.

Equipment and measurements

Paragraph Number 7 Measurements were taken using equipment and techniques described previously (7, 20). Exercise was performed using electromagnetically-braked cycle (Excalibur Sport; Lode, Groningen, The Netherlands) and arm-cranking (Angio; Lode, Groningen, The Netherlands) ergometers. During all tests participants wore a facemask (model 7940; Hans Rudolph, Missouri, USA) connected to a flow sensor (ZAN variable orifice pneumotach; Nspire Health, Oberthulba, Germany) that was calibrated using a 3 L syringe. Gas concentrations were measured using fast responding laser diode absorption spectroscopy sensors, which were calibrated using gases of known (5% CO_2, 15% O_2, balance N_2) concentration (BOC, Guilford, UK), and ventilatory and pulmonary gas exchange variables were determined breath-by-breath (ZAN 600USB; Nspire Health, Oberthulba, Germany). During all tests $\dot{V}O_2$ peak was defined as the highest recorded value over any 30 s period. Heart rate was measured using short-range telemetry (Polar S610;

Polar, Kempele, Finland) and arterial oxygen saturation was estimated (SpO_2) using a finger pulse oximeter (Model 8500; Nonin Medical, Minnesota, USA). Arterialized venous blood (6 mL) was drawn from a heated dorsal hand vein via an indwelling 21-G cannula. Blood was analyzed immediately for PCO_2 and pH (ABL520; Radiometer, Copenhagen, Denmark), and values were corrected for changes in rectal temperature (1000 Series Squirrel; Grant Instruments, Cambridge, UK). PCO_2 and pH were used to calculate plasma bicarbonate concentration ($[HCO_3^-]$) using the Henderson-Hasselbalch equation:

$$pH = pK + \log \frac{[HCO_3^-]}{0.03 \times PCO_2}$$

Plasma acid-base balance was examined using the physicochemical approach (20, 32), which describes the dependency of $[H^+]$ and $[HCO_3^-]$ on the three independent physicochemical variables: strong ion difference ([SID]), PCO_2, and the total concentration of weak acids ($[A_{tot}^-]$). Thus, a portion (5 mL) of each blood sample was immediately centrifuged for 10 min at 3000*g* and the plasma supernatant was removed. Plasma $[La^-]$ was subsequently determined using an automated analyzer (Biosen C_line Sport; EKF Diagnostics, Barleben, Germany). Plasma $[Na^+]$, $[K^+]$, and $[Cl^-]$ were determined using ion selective electrodes and total protein concentration ($[PPr^-]$) was assayed by immunoturbidimetry (ABX Pentra 400; Horiba, Northampton, UK). $[A_{tot}]$ was calculated as 2.45 × $[PPr^-]$ (30). Plasma strong ion difference ([SID]) was calculated as the sum of the strong cations minus the sum of the strong anions (32):

$$[SID] = ([Na^+] + [K^+]) - ([Cl^-] + [La^-])$$

During all trials blood samples were taken, and heart rate and SpO_2 were recorded, at rest, immediately before the prescribed cycling test (CYC_{ONSET}), and at the limit of cycling exercise tolerance (CYC_{END}).

Maximal incremental cycling test

Paragraph Number 8 Participants performed an incremental cycling test to the limit of tolerance, which was defined as the point at which cycling cadence fell below 60 rpm. Tests began at 0 W and power was increased by discrete 20 W increments every 60s. Cycling cadence was self-selected and matched during L_{INC} and AL_{INC}. Ventilatory and pulmonary gas exchange variables were averaged over 10s periods and the functional gain (i.e. slope of $\Delta \dot{V}O_2/\Delta W$) was determined, using linear regression, from 1 min into the incremental test up to either $\dot{V}O_2$ peak or where $\dot{V}O_2$ began to plateau (4). Maximum power output ($\dot{W}$ max) was calculated as the sum of the power output in the last completed stage plus the product of ramp increment (20 W) and the fraction of the final stage actually completed.

Power-duration relationship

Paragraph Number 9 The power-duration relationship was determined from four constant-power cycling tests performed to the limit of tolerance. Each participant adopted the same self-selected cycling cadence for all tests, which were terminated when cadence fell below 60 rpm. The initial L_{CONST} test was performed at 85% of the $\dot{W}$ max achieved during the preliminary L_{INC} test, and subsequent tests were performed at powers prescribed to elicit exercise intolerance over a range of times between approximately 3-15 min (19). Identical cycling powers were used during L_{CONST} and AL_{CONST} trials. CP and W' were estimated using the non-linear power-time model, and the linear work-time and power-(1/time) models. The power-(1/time) model was associated with the lowest SEE for the parameter estimates and was therefore chosen for further analysis (18).

Arm-cranking protocol

Paragraph Number 10 The arm-cranking protocol was adapted from that described previously (3, 26). Following a 5 min rest period participants performed eight 1 min arm-cranking exercise bouts, interspersed with 30s rest, at a work rate of 1.5-2.0 $W \cdot kg^{-1}$ body mass. The center of the arm-crank shaft was aligned to shoulder level and subjects were

seated in an upright position so that the elbow was slightly flexed when the hand was most distal. Cadence was maintained between 90-100 rpm. Consistent with the procedures of Nordsborg et al. (26), the final arm-cranking exercise bout was followed by a 4 min rest period, during which participants immediately transferred to the cycle ergometer in preparation for the prescribed cycling test. Ventilatory and pulmonary gas exchange variables were averaged over the final 30s of each arm-cranking exercise bout and over the final 30s of each minute during the 4 min rest period prior to the prescribed cycling test.

Statistical analyses

Paragraph Number 11 Data were analyzed using a two-way (trial x time) repeated measures ANOVA and Student's paired *t*-tests, as appropriate. Relationships between variables were examined using Pearson's product-moment correlation coefficient (*r*). Statistical significance was set at $P < 0.05$. Results are presented as mean ± SD unless otherwise stated.

Results

Physiological effects of arm-cranking exercise

Paragraph Number 12 All participants successfully completed the arm-cranking protocol. Physiological data at rest were pooled from all trials. Repeated measures ANOVA revealed no between-test differences in the ventilatory and pulmonary gas exchange responses to arm-cranking exercise ($P > 0.05$) and therefore these data were pooled. Furthermore, repeated measures ANOVA revealed no between-test differences in physiological responses at CYC_{ONSET} during L and AL trials ($P > 0.05$) and therefore data from L and AL trials were pooled separately. Ventilatory and pulmonary gas exchange responses during intermittent arm-cranking exercise, and during the 4 min rest period preceding the subsequent cycling test, are shown in Figure 1. During AL trials $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ were still elevated above rest at CYC_{ONSET} ($P < 0.01$). Heart rate, SpO_2 and plasma acid-base balance responses at CYC_{ONSET} are shown in Table 1. Heart rate was higher at CYC_{ONSET} during AL compared to

L (P < 0.01), whereas SpO_2 was not different between trials. Arm-cranking resulted in different plasma acid-base balance responses between L and AL trials at CYC_{ONSET}. Specifically, at CYC_{ONSET} $[Na^+]$ and $[La^-]$ were 3 and 10.4 mEq·L^{-1} higher (P < 0.05 and 0.01, respectively), $[Cl^-]$ was 2 mEq·L^{-1} lower (P < 0.05), and $[PPr^-]$ was 0.7 g·dL^{-1} higher (P < 0.01) during AL compared to L. These differences in plasma ions and $[PPr^-]$ affected the independent acid-base variables: [SID] was 5.4 mEq·L^{-1} lower, and $[A_{tot}]$ was 2.0 mEq·L^{-1} higher, during AL compared to L (P < 0.01). These differences in the independent acid-base variables also affected the dependent acid-base variables: $[H^+]$ was 12.7 nEq·L^{-1} higher, and $[HCO_3^-]$ was 7.4 mEq·L^{-1} lower, during AL compared to L (P < 0.01).

Paragraph Number 13 There was a tendency for the $\Delta \dot{V}O_2/\Delta W$ slope to be lower during AL_{INC} (9.3 ± 0.6 mL·min^{-1}·W^{-1}) compared to L_{INC} (10.5 ± 1.3 mL·min^{-1}·W^{-1}) (P = 0.06). Exercise duration (17.9 ± 0.8 vs. 16.6 ± 1.0 min), $\dot{W}$max (358 ± 15 vs. 332 ± 21 W), and $\dot{V}O_2$peak (4.31 ± 0.36 vs. 3.71 ± 0.44 L·min^{-1}) were lower during AL_{INC} compared to L_{INC} (P < 0.05). That a maximal effort was exerted during AL_{INC} is evidenced by all participants demonstrating a plateau in $\dot{V}O_2$, defined as an increase in $\dot{V}O_2$ of <50% of the expected increase for a 20 W increment as determined from each participant's $\Delta \dot{V}O_2/\Delta W$ slope ((29)). The reduction in $\dot{V}O_2$peak during AL_{INC} was not correlated with the reduced exercise duration (r = 0.52, P = 0.23) or $\dot{W}$max (r = 0.54, P = 0.22), but was correlated with the reduced $\Delta \dot{V}O_2/\Delta W$ slope (r = 0.75, P < 0.05). A representative example of the $\dot{V}O_2$ response to incremental exercise is shown in Figure 2.

Paragraph Number 14 At CYC_{END} heart rate was higher during L_{INC} compared to AL_{INC} (P < 0.01), whereas SpO_2 was not different between trials (Table 1). $[La^-]$ and $[K^+]$ were 2.4 and 0.48 mEq·L^{-1} higher during L_{INC} compared to AL_{INC} (P < 0.05), whereas there were no

differences between trials for the independent acid-base variables [SID], [A_{tot}] and PCO_2. The dependent acid-base variable [H^+] was 9.9 nEq·L^{-1} higher ($P < 0.01$), whereas [HCO_3^-] tended to be lower ($P = 0.08$), during L_{INC} compared to AL_{INC}.

Power-duration relationship and physiological responses at CYC_{END} during constant power exercise

Paragraph Number 15 Constant power exercise duration was 35 ± 15% shorter during AL_{CONST} compared to L_{CONST} trials ($P < 0.01$). The power-duration relationship was well described by the power-(1/time) model following both L_{CONST} (r^2 = 0.996 ± 0.003) and AL_{CONST} (r^2 = 0.993 ± 0.002) trials. CP was not different following L_{CONST} (267 ± 19 W, 95% confidence interval: -8 to 8 W) and AL_{CONST} (264 ± 20 W, 95% confidence interval: -10 to 11 W) trials. Conversely, W' was 32 ± 6% lower following AL_{CONST} (11.8 ± 4.2 kJ, 95% confidence interval: -2.7 to 2.6 kJ) compared to L_{CONST} (17.3 ± 5.7 kJ, 95% confidence interval: -3 to 3 kJ) trials ($P < 0.01$) (Fig. 3). The SEE was low for both CP (2 ± 2 and 3 ± 1 W, representing 0.9 ± 0.7 and 1.1 ± 0.5% of the mean CP following L_{CONST} and AL_{CONST} trials, respectively) and W' (0.93 ± 0.69 and 0.77 ± 0.42 kJ, representing 4.9 ± 2.1 and 6.3 ± 1.3% of the mean W' following L_{CONST} and AL_{CONST} trials, respectively). Furthermore, estimates of CP and W' from the power-(1/time) model were not different from those determined from the non-linear power-time model (L_{CONST}: 268 ± 21 W and 16.9 ± 6.4 kJ; AL_{CONST}: 262 ± 22 W and 12.7 ± 4.7 kJ) and linear work-time model (L_{CONST}: 267 ± 20 W and 17.0 ± 5.9 kJ; AL_{CONST}: 263 ± 21 W and 12.1 ± 4.5 kJ) and each pair of values was highly correlated following L_{CONST} (CP: r = 1.00; W': $r \geq 0.97$; $P < 0.01$) and AL_{CONST} (CP: r = 1.00; W': $r \geq 0.99$; $P < 0.01$) trials. The parameter estimates were therefore associated with low levels of uncertainty (19, 20).

Paragraph Number 16 The mean $\dot{V}O_2$peak was not different between L_{CONST} (4.11 ± 0.19 $L \cdot min^{-1}$) and AL_{CONST} (3.95 ± 0.35 $L \cdot min^{-1}$). Heart rate and SpO_2 at CYC_{END} were not different between L_{CONST} and AL_{CONST} (Table 1). Conversely, $[K^+]$ was 0.14 $mEq \cdot L^{-1}$ lower, and $[La^-]$ was 0.9 $mEq \cdot L^{-1}$ higher, during AL_{CONST} compared to L_{CONST} ($P < 0.05$). The absolute increase in $[K^+]$ from CYC_{ONSET} to CYC_{END} was similar between AL_{CONST} (0.61 ± 42 $mEq \cdot L^{-1}$) and L_{CONST} (0.66 ± 41 $mEq \cdot L^{-1}$), although the shorter exercise duration in AL_{CONST} meant that the rate of increase in $[K^+]$ was greater in AL_{CONST} (0.14 ± 0.13 $mEq \cdot L^{-1} \cdot min^{-1}$) compared to L_{CONST} (0.09 ± 0.08 $mEq \cdot L^{-1} \cdot min^{-1}$) ($P < 0.05$). At CYC_{END} $[PPr^-]$ was 0.3 $g \cdot dL^{-1}$ higher during AL_{CONST} compared to L_{CONST}, which resulted in a 0.7 $mEq \cdot L^{-1}$ higher $[A_{tot}]$ ($P < 0.05$). There were no differences between L_{CONST} and AL_{CONST} for the independent acid-base variables [SID] and PCO_2, or the dependent acid-base variables $[H^+]$ and $[HCO_3^-]$.

Discussion

Paragraph Number 17 Consistent with our hypothesis, the major finding of the present study was that prior severe-intensity upper body exercise reduced leg cycling W' without affecting CP. A novel aspect of the present study was that our experimental model allowed us to manipulate plasma, and presumably leg muscle, metabolite accumulation by performing prior upper body exercise. Although not measured in the present study, previous studies have reported constancy in leg intramuscular energy stores (ATP, phosphocreatine, and glycogen) following severe-intensity upper body exercise (2, 3). Therefore, the reduction in W' due to prior upper body exercise provides novel empirical support for the notion that the magnitude of W' is partly dependent on metabolite accumulation. Furthermore, the constancy of CP means that the reduced exercise tolerance during AL_{CONST} was exclusively dependent on the reduction in W', and, consistent with previous studies (13, 14, 27, 34), that the physiological bases of CP are insensitive to metabolite accumulation.

Paragraph Number 18 Existing empirical support for the notion that W' may depend on metabolite accumulation rather than intramuscular energy stores *per se* resides in a limited number of indirect observations. Firstly, during severe-intensity exercise intramuscular phosphocreatine concentration may decline to a minimum well before exercise intolerance ensues (33), and at the limit of severe-intensity exercise tolerance considerable reserve exists in intramuscular phosphocreatine (~10-40% of baseline) and ATP (~83% of baseline) concentrations (10, 13, 23, 33) (although depletion of individual muscle fibers is possible). Furthermore, continuation of exercise (via restoration of W') after the limit of severe intensity exercise tolerance has been reached is only possible if work-rate is reduced below CP (10, 11). Presumably this is because net clearance of fatigue-inducing metabolites can only occur at work rates below CP (10, 11), although restoration of intramuscular phosphocreatine may also play a role. Secondly, irrespective of work-rate, the limit of tolerance during severe-intensity exercise is associated with a consistent, and thus potentially "critical", intramuscular pH and concentrations of inorganic phosphate and ADP (33). Thirdly, the recovery kinetics of $\dot{V}O_2$ (a proxy for intramuscular phosphocreatine recovery) following severe-intensity exercise are slower than the recovery kinetics of W' (13). Lastly, whilst leg intramuscular energy stores are unaffected by inspiratory muscle training, blood $[La^-]$ and $[H^+]$ are attenuated (7) and W' is increased in the absence of a change in CP (21).

Paragraph Number 19 Although these observations collectively suggest that W' may depend on metabolite accumulation, to our knowledge no previous study has characterized the power-duration relationship following the discrete manipulation of fatigue-inducing metabolites. Interestingly, when prior severe-intensity cycling exercise was performed before the criterion cycling exercise (i.e. the same muscle groups were used for both prior and criterion exercise) W' was reduced by broadly the same extent (-34%) as the current findings (-32%) and CP was also unchanged (14). Despite dissimilar prior exercise protocols the

reductions in W' followed broadly similar changes in the metabolic milieu: immediately prior to the constant power cycling tests used to determine the power-duration relationship plasma [La^-] was 11.6 $mEq \cdot L^{-1}$ in the current study whereas whole blood [La^-] was 8.6 $mEq.L^{-1}$ in the study of Ferguson et al. (14). It may seem surprising, therefore, that W' was not reduced to a greater extent following prior exercise using the same muscle groups because in addition to metabolite accumulation partial depletion of leg intramuscular energy stores must have also occurred. Consequently, resolving the relative impact of these two factors on reducing W' is not possible and represents a limitation of the work of Ferguson et al. (14). Comparison of these studies is further complicated because "priming" effects resultant from prior exercise differ depending on whether the same (large influence) or different (negligible influence) muscle groups are used in the priming and criterion exercise bouts (16). Our experimental model allowed us to avoid the priming effect associated with prior exercise using the same muscles and presumably retain the leg intramuscular energy stores at CYC_{ONSET} (2, 3). Therefore, by discretely manipulating the temporal profile of plasma and, presumably, leg muscle metabolite accumulation during subsequent cycling exercise our findings provide novel empirical support for the notion that W' at least partially depends on the accumulation of fatigue-inducing metabolites.

Paragraph Number 20 The mechanism(s) by which prior upper body exercise affects leg cycling exercise tolerance and hence W' may partly reside in the effect of elevated plasma metabolites on previously resting leg muscle function (8). Although intracellular acidosis has long been considered a key mediator of muscle fatigue during severe-intensity exercise (15), this view has been challenged (3, 8, 26). Conversely, muscle fatigue during severe-intensity exercise has been causatively linked with an increased interstitial [K^+], which induces a loss of excitability and contractility (8). Using the microdialysis technique Nordsborg et al. (26) demonstrated a similar interstitial [K^+] at the onset of single leg knee extensor exercise during

L and AL. However, during leg exercise K^+ efflux from the active muscle, and increases in interstitial [K^+], were accelerated during AL compared to L and exercise tolerance was reduced. Consistent with these observations, we observed an accelerated increase in plasma [K^+] during AL_{CONST} compared to L_{CONST}. However, muscle fatigue is a multifaceted process (1, 8, 15) that is difficult to resolve based on humoral measures *per se*, and greater insight into the mechanism(s) by which W' is reduced during AL would come from studies utilising interstitial measurements, muscle biopsies or ^{31}P magnetic resonance spectroscopy. Using the latter technique Vanhatalo et al. (33) have shown that the limit of tolerance during severe-intensity knee extensor exercise coincides, irrespective of the work-rate, with the attainment of consistently low values of intramuscular phosphocreatine concentration and pH. Whether the limit of severe-intensity cycling exercise tolerance, following prior upper body exercise, is also associated with a consistent "critical" intramuscular milieu thus provides an interesting avenue for future investigation.

Paragraph Number 21 Exercise duration was 7% shorter during AL_{INC} compared to L_{INC}, which is considerably less than the 35% shorter exercise duration observed during AL_{CONST} compared to L_{CONST}. This difference may be attributed to the duration spent at sub-CP exercise intensities during the incremental exercise test, which would have prolonged the recovery period and thus increased restoration of W' (13). Nevertheless, exercise duration/ $\dot{W}$ max, $\dot{V}O_2$ peak, and the $\Delta \dot{V}O_2 / \Delta W$ slope were still lower during AL_{INC} compared to L_{INC}. These findings contrast those of Boone et al. (5) who reported no change in these parameters during incremental cycling exercise preceded by maximal incremental arm-cranking exercise. However, compared to the present study, Boone et al. (5) used a longer intervening recovery period (6 min rest followed by 3 min of cycling at 50 W) and blood [La^-] at CYC_{ONSET} (8.4 $mEq \cdot L^{-1}$) was lower, which may explain these differences.

Paragraph Number 22 Elucidating the physiological mechanisms responsible for the lower $\Delta \dot{V}O_2/\Delta W$ slope and $\dot{V}O_2$ peak during AL_{INC} compared to L_{INC} was beyond the scope of the present study and therefore the reasons for these observations remain unclear. The $\dot{V}O_2$ response to incremental cycling exercise is known to depend on changes in muscle blood flow (i.e. oxygen transport) and muscle fiber recruitment (i.e. oxygen utilization) (6). Indeed, during incremental exercise $\Delta \dot{V}O_2/\Delta W$ and $\dot{V}O_2$ peak are reduced when oxygen transport is limited by breathing hypoxic air (35), whereas $\dot{V}O_2$ during constant power exercise is reduced by prior preferential fatigue or glycogen depletion of type II muscle fibers (9, 12). These observations indicate that the lower $\dot{V}O_2$ response during AL_{INC} compared to L_{INC} may be explained by a limitation in oxygen transport and/or utilization, although further research is necessary to elucidate their relative contributions and the mechanism(s) by which they are influenced by prior upper body exercise.

Paragraph Number 23 In conclusion, prior severe-intensity upper body exercise reduced leg cycling W' without affecting CP. This finding therefore provides novel empirical support for the notion that the magnitude of W' is partly dependent on metabolite accumulation, rather than a finite energy store *per se*.

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TABLE 1. Physiological responses at rest, immediately prior to cycling exercise (CYC_{ONSET}), and at the limit of cycling exercise tolerance (CYC_{END}) during incremental (INC) and constant power (CONST) exercise. Data in column 'Rest' reflects pooled data from all trials. Data in columns 'L' and 'AL' reflect data pooled separately from all trials performed without (L) and with (AL) prior arm-cranking exercise. Data are mean ± SD.

	Rest	CYC_{ONSET}		CYC_{END}			
		L	AL	L_{INC}	AL_{INC}	L_{CONST}	AL_{CONST}
Heart rate (bpm)	63 ± 11	61 ± 11	96 ± 9††	181 ± 9	173 ± 11**	171 ± 12	171 ± 11
SpO_2 (%)	98 ± 1	98 ± 1	97 ± 0	95 ± 1	96 ± 1	95 ± 1	95 ± 2
Plasma ions and [PPr^-]							
[Na^+] (mEq·L^{-1})	138 ± 3	138 ± 2	141 ± 3†	143 ± 2	142 ± 2	142 ± 2	143 ± 3
[K^+] (mEq·L^{-1})	3.99 ± 0.09	3.93 ± 0.11	3.86 ± 0.13	5.12 ± 0.47	4.64 ± 0.33*	4.60 ± 0.30	4.46 ± 0.30^{+}
[La^-] (mEq·L^{-1})	1.2 ± 0.1	1.2 ± 0.1	11.6 ± 2.9††	15.5 ± 1.7	13.1 ± 2.0*	15.3 ± 2.6	16.2 ± 2.6^{++}
[Cl^-] (mEq·L^{-1})	103 ± 2	103 ± 1	101 ± 1†	103 ± 2	103 ± 2	102 ± 1	102 ± 1
[PPr^-] (g·dL^{-1})	7.0 ± 0.4	7.0 ± 0.4	7.7 ± 0.4††	7.9 ± 0.4	7.9 ± 0.2	7.8 ± 0.3	8.1 ± 0.4^{+}
Independent acid-base variables							
[SID] (mEq·L^{-1})	38.0 ± 1.8	37.8 ± 1.8	32.4 ± 2.0††	29.8 ± 1.5	31.1 ± 1.7	29.5 ± 1.8	29.8 ± 1.6
[A_{tot}] (mEq·L^{-1})	17.2 ± 0.9	17.0 ± 0.9	19.0 ± 1.0††	19.4 ± 1.0	19.3 ± 0.6	19.1 ± 0.8	19.8 ± 1.1^{+}
PCO_2 (mmHg)	43.0 ± 2.1	43.4 ± 2.6	40.6 ± 3.0	37.8 ± 3.5	36.1 ± 4.8	38.0 ± 4.3	37.4 ± 4.6
Dependent acid-base variables							
[H^+] (nEq·L^{-1})	40.0 ± 0.9	40.4 ± 1.3	53.1 ± 4.3††	60.8 ± 3.4	50.9 ± 3.3**	60.8 ± 6.6	60.9 ± 7.1
[HCO_3^-] (mEq·L^{-1})	25.6 ± 0.7	25.7 ± 0.7	18.3 ± 1.9††	14.9 ± 1.6	17.0 ± 2.5	15.0 ± 2.1	14.8 ± 2.1

Different from L ($^{\dagger}P < 0.05$, $^{\dagger\dagger}P < 0.01$). Different from L_{INC} ($^{*}P < 0.05$, $^{**}P < 0.01$). Different from L_{CONST} ($^{+}P < 0.05$, $^{++}P < 0.01$).

Figure Captions

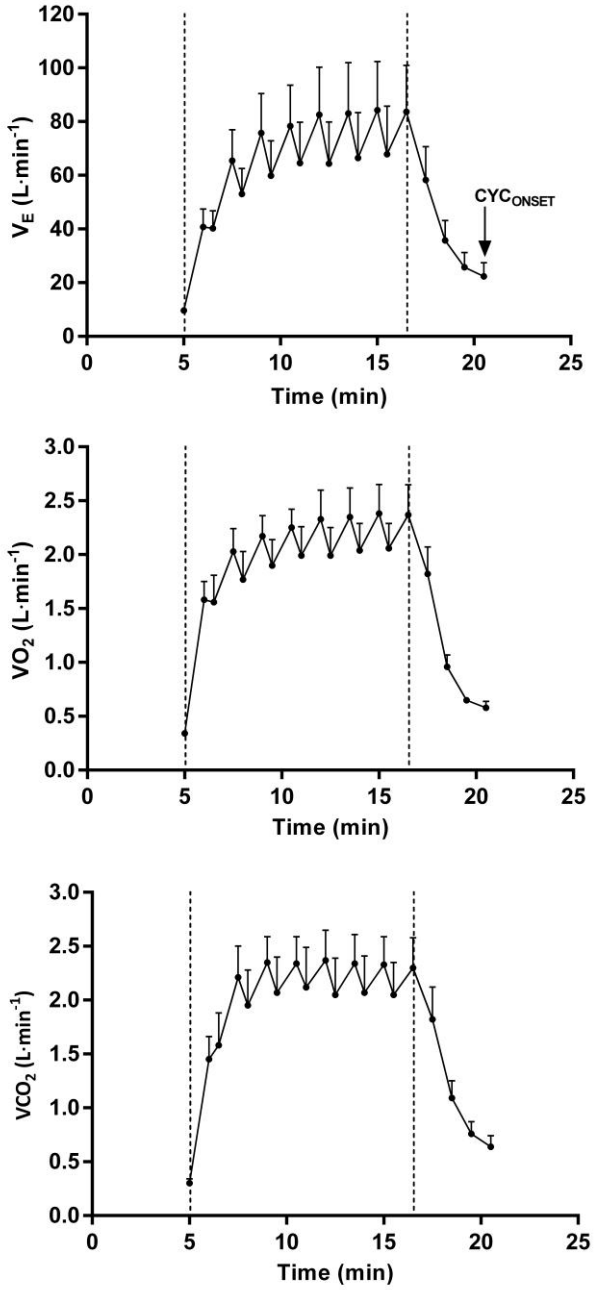

FIGURE 1-Ventilatory and pulmonary gas exchange responses to intermittent arm-cranking exercise. Dashed vertical lines represent the start and end of the arm-cranking protocol. Data points are mean ± SD and reflect the mean responses over the final 30s of each arm-cranking exercise bout and over the final 30s of each minute during the 4 min rest period prior to the prescribed cycling test.

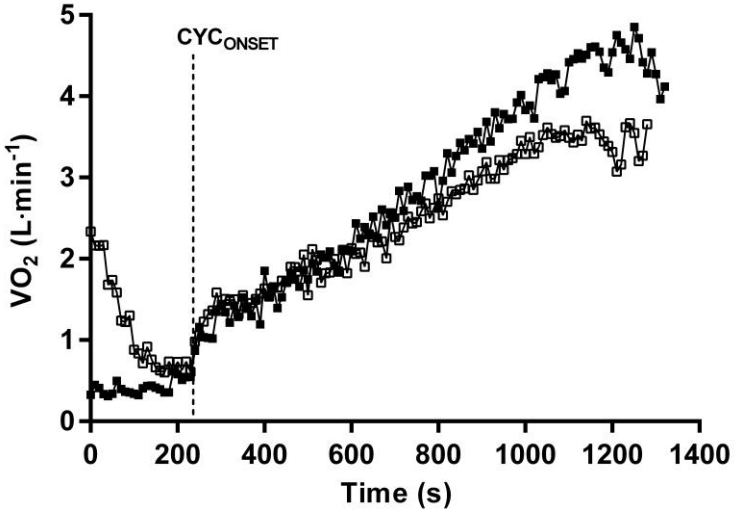

FIGURE 2- $\dot{V}O_2$ responses from a representative participant during L_{INC} (■) and AL_{INC} (□). Note the lower $\dot{V}O_2$ slope and $\dot{V}O_2$ peak during AL_{INC} compared to L_{INC}.

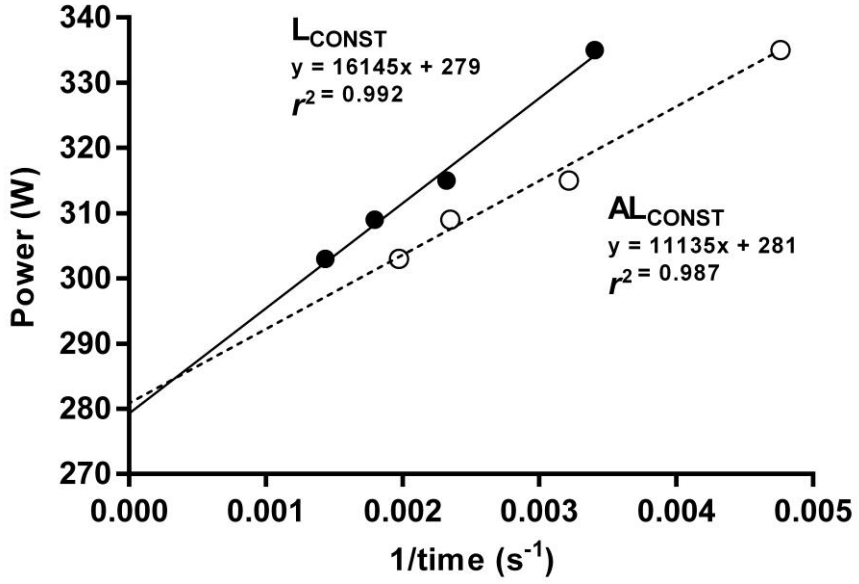

FIGURE 3-The power-duration relationship in a representative participant following L_{CONST} (•) and AL_{CONST} (o) trials. CP and W' are denoted by the y-intercept and slope, respectively, of the linear regression.

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