PRIOR EXERCISE SPEEDS PULMONARY OXYGEN UPTAKE KINETICS AND INCREASES CRITICAL POWER DURING SUPINE BUT NOT UPRIGHT CYCLING

RICHIE P. GOULDING[1]; DENISE M. ROCHE[1]; SIMON MARWOOD[1]

[1]School of Health Sciences, Liverpool Hope University, Hope Park Campus, Liverpool, Merseyside, L16 9JD, United Kingdom

Running head: Oxygen uptake kinetics and critical power

Correspondence:

Simon Marwood, Ph.D.

Email: marwoos@hope.ac.uk

Telephone: 0151 291 3629

Address Correspondence: Liverpool Hope University, Hope Park Campus, Liverpool, L16 9JD

New Findings

- **What is the central question of this study?**

  Critical power (CP) represents the highest work-rate for which a metabolic steady-state is attainable. The physiological determinants of CP are unclear, however research suggests that CP may be related to the time constant of phase II oxygen uptake kinetics ($\tau_{\dot{V}O2}$).

- **What is the main finding and its importance?**

  We provide the first evidence that $\tau_{\dot{V}O2}$ is mechanistically related to CP. A reduction of $\tau_{\dot{V}O2}$ in the supine position was observed alongside a concomitant increase in CP. This effect may be contingent on measures of oxygen availability derived from near-infrared spectroscopy.

Abstract

Critical power (CP) is a fundamental parameter defining high-intensity exercise tolerance and is related to the time constant of phase II pulmonary oxygen uptake kinetics ($\tau_{\dot{V}O2}$). To test the hypothesis that this relationship is causal we determined the impact of prior exercise ("priming") on CP and $\tau_{\dot{V}O2}$ in the upright and supine positions. 17 healthy men were assigned to either upright or supine exercise groups, whereby CP, $\tau_{\dot{V}O2}$ and muscle deoxyhaemoglobin kinetics ($\tau_{[HHb]}$) were determined via constant-power tests to exhaustion at four work-rates with (primed) and without (control) priming exercise at ~31%Δ. During supine exercise, priming reduced $\tau_{\dot{V}O2}$ (control*:* 54 ± 18 vs. primed*:* 39 ± 11 s; $P < 0.001$), increased $\tau_{[HHb]}$ (control: 8 ± 4 vs. primed: 12 ± 4 s; $P = 0.003$) and increased CP (control: 177 ± 31 vs. primed*:* 185 ± 30 W, $P = 0.006$) compared to control. However, priming exercise had no effect on $\tau_{\dot{V}O2}$ (control*:* 37 ± 12 *vs.* primed*:* 35 ± 8 s; $P = 0.82$), $\tau_{[HHb]}$ (CON: 10 ± 5 s vs. PRI: 14 ± 10; $P = 0.10$), or CP (control*:* 235 ± 42 vs. primed*:* 232 ± 35 W; $P = 0.57$) during upright exercise. The concomitant reduction of $\tau_{\dot{V}O2}$ and increased CP following priming in the supine group, effects that were absent in the upright group, provides the first experimental evidence that $\tau_{\dot{V}O2}$ is mechanistically related to critical power. The increased $\tau_{[HHb]}$ suggests that this effect was mediated, at least in part, by improved oxygen availability.

Keywords: critical power, exercise tolerance, oxidative metabolism, oxygen uptake kinetics, power-duration relationship, priming exercise.

Introduction

The potential to tolerate high-intensity exercise underpins endurance performance (Burnley & Jones, 2007), is an important contributor to quality of life in a wide range of chronic diseases (Kaplan *et al.* 1987; Marchionni *et al.* 2003; Reis *et al.* 2013), and is a strong predictor of clinical outcomes (Belardinelli *et al.* 1999). A detailed understanding of the underpinning physiological mechanisms is therefore important for the design of interventions aimed at maintaining or enhancing high-intensity exercise tolerance.

During high-intensity cycle exercise, a hyperbolic relationship between external power and tolerable exercise duration (the power-duration relationship; Monod & Scherrer, 1965) accurately characterises exercise tolerance for various exercise modalities and durations spanning ~2-30 minutes in humans (Hill, 1993) and various other species (e.g. Billat *et al*. 2005; Copp *et al.* 2010). The asymptote of this relationship is known as critical power, with W' being the curvature constant that is mathematically equivalent to a fixed quantity of work that can be performed above critical power (Monod & Scherrer, 1965; Moritani *et al.* 1981; Poole *et al*. 1988).

Critical power represents the maximal metabolic rate at which a steady-state can be attained for arterial blood acid-base status [hydrogen ions (H^+), lactate (L^-), and bicarbonate], pulmonary oxygen uptake ($\dot{V}O_2$), and intramuscular phosphate [phosphocreatine (PCr) and inorganic phosphate (P_i)] (Jones *et al*. 2008; Poole *et al.* 1988; Vanhatalo *et al.* 2016). When exercising above critical power, progressive metabolic contributions from non-oxidative sources (i.e. stored muscle [PCr], glycolysis/glycogenolysis with consequent L^- production) are apparent (Jones *et al.* 2008; Poole et al. 1988; Vanhatalo *et al.* 2010), resulting in the accumulation of fatigue-related metabolites (i.e. [H^+],

intramuscular [P_i], interstitial [K^+], for review see Allen, Lamb, & Westerblad, 2008). As a consequence, there is an inexorable increase in $\dot{V}O_2$ until its maximally attainable value ($\dot{V}O_2$ max) is reached, with exhaustion ensuing shortly thereafter (Poole *et al.* 1988). Hence, critical power demarcates the upper boundary of energy provision that is wholly oxidative, i.e. without progressive anaerobic metabolic contribution (Barker *et al.* 2006; Chidnok *et al.* 2013*b*; Coats *et al.* 2003). Indeed, critical power is strongly related to markers of aerobic fitness such as $\dot{V}O_2$ max (McNaughton & Thomas, 1996), O_2 delivery (Broxterman *et al.* 2014; 2015; Vanhatalo *et al.* 2010), type 1 muscle fibre type composition (Vanhatalo *et al.* 2016), and pulmonary $\dot{V}O_2$ kinetics (Murgatroyd *et al.* 2011). However, the precise physiological determinants underpinning these relationships remain to be elucidated.

When transitioning from rest to exercise, following a short delay, which reflects the muscle-to-lung transit time, $\dot{V}O_{2,}$ rises exponentially to match the steady-state ATP requirements in the muscle (Whipp *et al.* 1982). Murgatroyd et al. (2011) showed that the time constant of the phase II (fundamental phase) of pulmonary $\dot{V}O_2$ kinetics ($\tau_{\dot{V}O2}$) was strongly related to critical power. These authors suggested that a decreased $\tau_{\dot{V}O2}$ would reduce the reliance on non-oxidative metabolism, thus attenuating muscle metabolic perturbation during the exercise transition. Hence, a higher power is attained for a given magnitude of oxygen deficit accumulation, therefore explaining a causal relationship between $\tau_{\dot{V}O2}$ and critical power. However, critical power and $\tau_{\dot{V}O2}$ are both improved with endurance training (Carter *et al.* 2000; Gaesser & Wilson, 1988; Jenkins & Quigley, 1993; Jones & Carter, 2000; Marwood *et al.* 2010), hence whether $\tau_{\dot{V}O2}$ is an independent determinant of critical power, or the association between the two parameters results from other shared physiological processes related to training status, remains to be determined.

One such way to address the independency of these relationships is with a prior bout of high-intensity "priming" exercise, which can acutely alter pulmonary $\dot{V}O_2$ kinetics independently of any chronic adaptations that influence critical power. However, the manner in which the $\dot{V}O_2$ kinetics are altered is dependent upon factors such as aerobic fitness, exercise mode and the sufficiency of oxygen availability to meet the ATP demands in any given condition (Burnley *et al*. 2000; Gurd *et al*. 2005; Jones *et al*. 2006). Specifically, in the upright position priming exercise reduces $\tau_{\dot{V}O2}$ by a magnitude that is linearly related to its control value (Gurd *et al.* 2005), such that those individuals with "slow" $\dot{V}O_2$ kinetics will demonstrate a greater reduction in $\tau_{\dot{V}O2}$ in the primed condition. Conversely, individuals with fast $\dot{V}O_2$ kinetics (i.e. low $\tau_{\dot{V}O2}$) will demonstrate little (Gurd *et al.* 2005) or no (Burnley *et al.* 2000) reduction in this parameter following priming exercise, with no effect on critical power (Burnley *et al.* 2011; Jones *et al.* 2003). Such individuals are typically characterised as being young and aerobically fit, with the result of priming exercise instead being a blunting of the "slow component" of pulmonary $\dot{V}O_2$ kinetics and an increase in W' (Burnley *et al.* 2011; Jones *et al*. 2003). In contrast, in the supine position where $\tau_{\dot{V}O2}$ is normally greater than in the upright position (Hughson *et al.* 1991; Koga *et al.* 1999), priming exercise reduces $\tau_{\dot{V}O2}$, an effect likely due to the supine position imposing an oxygen availability limitation that is negated by the right-shifted oxyhaemoglobin curve and improved muscle perfusion that accompanies prior exercise (Jones *et al.* 2006). Given the previously established association between $\tau_{\dot{V}O2}$ and critical power (Murgatroyd *et al.* 2011), it is therefore possible that in young, aerobically fit individuals, priming exercise will decrease $\tau_{\dot{V}O2}$ and thus enhance critical power in the supine, but not upright, body positions. Such evidence would implicate $\tau_{\dot{V}O2}$ as an independent determinant of critical power.

The aim of the present study was therefore to examine the effect of priming exercise on critical power and $\tau_{\dot{V}O2}$ in the upright and supine body positions. We hypothesised that (i) priming exercise would reduce $\tau_{\dot{V}O2}$ in the supine but not upright positions, (ii) priming exercise would increase critical power in supine but not upright positions, and (iii) critical power would be significantly correlated with $\tau_{\dot{V}O2}$ in both body positions. In order to provide insight into the physiological mechanisms underpinning these effects, heart rate and muscle deoxygenation kinetics were also determined, the latter via the deoxyhaemoglobin signal obtained from near-infrared spectroscopy which reflects the balance between oxygen delivery and utilization within the field of interrogation.

MATERIALS & METHODS

Ethical Approval. The study was conducted according to the declaration of Helsinki and all procedures were approved by the Liverpool Hope University Research Ethics Committee. Rights to confidentiality, withdrawal and benefits/risks of the protocol were explained prior to participation and all participants provided written informed consent.

Participants. 17 healthy male participants volunteered for the study. Participants were recreationally active but not highly trained. Participants were placed in either the upright (mean ± SD, age = 34 ± 10 years; height = 181 ± 8 cm; mass = 79 ± 10 kg; *n* = 10) or the supine (mean ± SD, age = 29 ± 7 years; height = 177 ± 9 cm; mass = 77 ± 9 kg; *n* = 10) exercise groups, with 3 participants completing both groups. Participants were instructed not to consume alcohol or perform strenuous exercise within the 24 h preceding each exercise test, not to consume caffeine within the preceding 6 h, and to arrive 3 h postprandial.

Procedures. Testing was conducted in a well-ventilated laboratory that was maintained between temperatures of 18-21^{o}C. Participants visited the laboratory on 9 occasions over a 3-6-week period, with each test scheduled at the same time of day (±2 h) and with at least 24 h separating visits. Participants completed one preliminary trial and eight experimental trials. Exercise tests were performed on an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) for the upright group. Saddle height/ angle and handlebar height/angle were recorded at the first test and replicated during each subsequent test. For the supine group, participants cycled using an electronically braked ergometric unit (Lode Angio, Groningen, The Netherlands) whilst lying flat on an Echo Cardiac Stress Table (Lode, Groningen, The Netherlands). Hand rails were available for participants to grip throughout the tests to minimise backwards movement when forces were applied to the pedals, and an adjustable shoulder pad was positioned above the participant's shoulder to further prevent backward movements. Participant's feet were strapped securely to the pedals. The position of the shoulder pad and the distance between the hip and the crank was recorded and replicated during each visit. Throughout all upright and supine exercise tests, participants were instructed to maintain a cadence of 80 rev/min, and exhaustion was defined as when the participant's cadence dropped below 70 rev/min. Time to exhaustion was measured to the nearest second in all tests.

Preliminary trial. Participant's height and weight were recorded upon arrival at the lab, prior to undertaking an incremental ramp test until the limit of tolerance to establish $\dot{V}O_2$ max, gas exchange threshold (GET), and the power outputs for subsequent tests. The exercise test consisted of 3-minutes of baseline pedalling at 30 W, followed by a continuous, ramped increase in work rate of 30 W.min^{-1} until the limit of tolerance. Gas exchange and ventilatory

variables were measured at the mouth continuously throughout each test. $\dot{V}O_2$ max was defined as the highest $\dot{V}O_2$ value measured over 30 s. Though we did not perform a verification trial, previous research has shown that the incremental/ramp cardiopulmonary exercise test produces highly reproducible measures of $\dot{V}O_2$ max in this population (Chidnok et al. 2013*a*; Poole & Jones, 2017). The GET was measured as a non-invasive estimate of the lactate threshold via visual inspection of the data using a cluster of predefined criteria; including 1) a disproportionate rise in CO_2 production ($\dot{V}CO_2$) relative to $\dot{V}O_2$; 2) an increase in minute ventilation ($\dot{V}E$) relative to $\dot{V}O_2$ ($\dot{V}E/\dot{V}O_2$) without an increase in $\dot{V}E$ relative to $\dot{V}CO_2$ ($\dot{V}E/\dot{V}CO_2$); and 3) an increase in end tidal O_2 tension without decreasing end tidal CO_2 tension. The mean response time (MRT) of $\dot{V}O_2$ during ramp exercise was taken into account utilising a slight modification of the procedures described by Boone *et al.* (2008). Briefly, the linear regression line of the $\dot{V}O_2$-time relationship was determined, with the first 120 s and last 180 s removed so as to isolate the linear portion of the relationship. The MRT was defined as the time between the beginning of the ramp test and the intersection between baseline $\dot{V}O_2$ ($\dot{V}O_{2b}$) and backwards extrapolation of the regression line of the $\dot{V}O_2$-time relationship. $\dot{V}O_{2b}$ was calculated as the average $\dot{V}O_2$ measured over the final 30 s of the baseline period. Work rates for subsequent tests were therefore calculated using the linear regression of the $\dot{V}O_2$-time relationship and solving for $\dot{V}O_2$, with account taken of the MRT.

Experimental trials. For the following eight visits in both the upright and supine groups, participants were required to exercise to exhaustion at four fixed power outputs on two occasions, each with and without a bout of "priming" exercise. The power output of these bouts of exercise were selected based upon performance during the preliminary exercise test and calculated to be in the range of 50%Δ (i.e. a work rate calculated to require 50% of

the difference between the GET and $\dot{V}O_2$ max) to 110% $\dot{V}O_2$ max. The goal of this range of power outputs was to produce a range of exercise tolerances within the range of 2-15 minutes. These power outputs are subsequently referred to as WR 1, WR 2, WR 3, and WR 4, with WR 1 being the lowest and WR 4 being the highest power outputs, respectively. Where necessary, adjustments were made to the required power output of subsequent exercise tests based upon performance in the initial tests. The order of intensities was randomised and participants alternated between conditions in order to prevent any order effect. Each intensity was performed once in each condition; i.e. once with priming exercise (PRI) and once without priming exercise (CON). CON consisted of 3 minutes of baseline pedalling at 20 W, after which an instantaneous step increase to the required power output was abruptly applied, and participants exercised until the limit of tolerance. In PRI, participants performed 3 minutes of baseline pedalling at 20 W before an instantaneous step increase to a power output of 40%Δ for 6 minutes. This power output was selected in order to yield a heavy exercise intensity (i.e. between the GET and critical power). On occasions where the power output for priming exercise was deemed not to be heavy (based upon the $\dot{V}O_2$ and blood [L^-] profiles), that test was repeated on a separate occasion with the power output for the priming bout being modified. Upon completion of this priming bout of exercise, participants rested quietly on the ergometer for 7 minutes, before performing a further 3 minutes of baseline pedalling at 20 W (providing 10 minutes of rest between priming and the subsequent constant work rate bouts) and subsequently, an instantaneous step increase to the required power output was abruptly applied until the limit of tolerance was reached.

During all exercise tests, pulmonary gas exchange and ventilation were measured breath-by-breath with subjects using a metabolic cart (Blue Cherry, Geratherm Respiratory, GmbH, Germany). Participants wore a silicone facemask (Hans Rudolph, Kansas, United States) of known dead space attached to a low-dead space flow sensor (Geratherm Respiratory, GmbH, Germany). The metabolic cart was connected to the participant via a capillary line connected to the flow sensor. The gas analysers were calibrated before each test using gases of known concentrations and the flow sensors were calibrated using a 3-liter syringe (Hans Rudolph, Kansas City, MO). Heart rate was measured every 1 s during all tests using short-range radiotelemetry (Garmin FR70, Garmin Ltd., Switzerland). For both CON and PRI, blood was sampled from a fingertip into glass capillary tubes at rest, during the last minute of baseline pedalling preceding the exhaustive constant work rate bout, and immediately following exhaustion. Whole blood [L^-] was determined using a Biosen lactate analyser (Biosen C-Line, EKF, Germany).

During the experimental trials, continuous non-invasive measurements of muscle oxygenation/deoxygenation status were made via a frequency-domain multidistance near-infrared spectroscopy (NIRS) system (Oxiplex TS, ISS, Champaign, USA). The OxiplexTS uses one light-emitting diode (LED) detector fibre bundle and eight LEDs functioning at wavelengths of 690 and 830 nm (four LEDs per wavelength). Light-source detector separation distances of 2.25 – 3.75 cm for each wavelength were utilised with cell water concentration assumed constant at 70% and data sampled at 2 Hz. This NIRS device measures and incorporates the dynamic reduced scattering coefficients to provide absolute concentrations (μM) of deoxygenated haemoglobin + myoglobin ([HHb+Mb]), which may be regarded as relatively unaffected by changes in blood volume during acute exercise (De Blasi

et al. 1993; Ferrari *et al.* 1997; Grassi *et al.* 2003). NIRS has previously been shown to produce valid estimates of O_2 extraction (De Blasi *et al.* 1993; DeLorey *et al.* 2003; Ferrari et al. 1997; Ferreira *et al.* 2006; Grassi *et al.* 2003). The absorption spectrum of myoglobin [Mb] overlaps that of [HHb]; therefore presently NIRS is unable to determine the relative contribution of myoglobin [Mb] to the overall NIRS signal (De Blasi et al. 1991). In referring to the NIRS deoxygenation signal as [HHb+Mb], the contribution of [Mb] is therefore also acknowledged. Additionally, the NIRS device provides measures of [oxygenated haemoglobin + myoglobin] ([HbO_2+MbO_2]) and [total haemoglobin + myoglobin] ([THb+Mb]) concentration (as [HbO_2+MbO_2] + [HHb+Mb]) and thus, O_2 availability. The flexible NIRS probe was placed longitudinally along the belly of the right vastus lateralis muscle midway between the greater trochanter and the lateral condyle of the tibia and marked with washable pen such that the probe position could be replicated for each subsequent visit. The probe was held firmly in place by elastic Velcro strapping. Following each trial, indentations of the probe on the participant's skin were inspected to confirm that the probe had not moved during the trial, which was the case for every exercise transition. The NIRS probe was calibrated prior to each testing session using a calibration block of known absorption and scattering coefficients. Calibration was then cross-checked using a second block of known but distinctly different absorption and scattering coefficients. Each of these procedures was according to the manufacturer's recommendations.

Data analysis. The breath-by-breath $\dot{V}O_2$ data from each constant work rate exercise bout were initially examined to exclude errant breaths due to coughs, swallows, sighs etc. identified as atypical of the underlying response by removing values lying more than four standard deviations from the local mean determined using a 5-breath rolling average.

Edited $\dot{V}O_2$ data were then subsequently linearly interpolated to provide second-by-second values. For $\dot{V}O_2$ responses to the bouts of priming exercise in PRI, the four transitions were also time-aligned and ensemble averaged to produce a single dataset; whereas the criterion bout for the determination of critical power and W' in each condition were not repeated, hence each of these were modelled independently. For each exercise transition, data preceding a precipitous drop in respiratory exchange ratio and end-tidal O_2 pressure were excluded to remove the phase I (cardiodynamic) response (Whipp & Ward, 1990) and a monoexponential model (Eq. 1) with time delay was then fitted to the data:

$$\dot{V}O_{2\,(t)} = \dot{V}O_{2\,(b)} + A_{VO2} * (1 - e^{-(t - TD_{VO2}/\tau_{VO2})}) \quad (1)$$

Where $\dot{V}O_{2\,(t)}$ is the $\dot{V}O_2$ at any time *t*; $\dot{V}O_{2\,(b)}$ is the baseline $\dot{V}O_2$ which was taken as the mean $\dot{V}O_2$ from the last 30 s of the baseline period preceding the criterion bout, $A_{\dot{V}_{O2}}$ is the amplitude of the fundamental response, $TD_{\dot{V}_{O2}}$ is the time delay of the fundamental response relative to the onset of exercise, and $\tau_{\dot{V}O2}$ is the time constant of the fundamental response. The onset of the $\dot{V}O_2$ slow component ($TD_{S\dot{C}V_{O2}}$) was determined using purpose designed programming in Microsoft Excel (Microsoft Corporation, Redmond, WA) which iteratively fits a mono-exponential function to the $\dot{V}O_2$ data, starting at 60s until the window encompasses the entire response. The resulting fundamental phase time constants are plotted against time and the $TD_{S\dot{C}V_{O2}}$ was identified as the point at which the fundamental phase time constant consistently deviates from a previously "flat" profile, and the demonstration of a local threshold in the X^2 value (Rossiter *et al.* 2001). This method allows the fitting of Eq. 1 to the fundamental component of the response isolated from the slow component, thus avoiding the possibility of arbitrarily parameterizing the slow component. The isolated fundamental responses were then fitted with the same monoexponential

model as shown in Eq. 1 using Origin 6.0 (OriginLab Corporation, MA, USA) to obtain the 95% confidence intervals for the derived parameter estimates. The amplitude of the $\dot{V}O_2$ slow component was determined by calculating the difference between the end exercise $\dot{V}O_2$ (i.e. mean $\dot{V}O_2$ over final 30 s of exercise) and $A_{\dot{V}_{O2}}$+$\dot{V}O_{2\,(b)}$. The functional gain of the fundamental $\dot{V}O_2$ response was also calculated by dividing $A_{\dot{V}_{O2}}$ by the change in work rate (i.e. $A_{\dot{V}_{O2}}$/Δ work rate).

The NIRS derived [HHb+Mb] responses to exercise were also modelled to provide information on muscle deoxygenation kinetics. Since the [HHb+Mb] signal increases after a short delay in response to step exercise, the time delay before the onset of the exponential rise in [HHb+Mb] (i.e. $TD_{[HHb+Mb]}$) was defined as a 1 SD increase in [HHb+Mb] above the mean baseline value taken from the final 30 s of baseline cycling (DeLorey et al. 2003). In instances where [HHb+Mb] decreased after the exercise onset, $TD_{[HHb+Mb]}$ was taken as the first point following the nadir showing a continual increase in [HHb+Mb]. After removing data prior to this point, [HHb+Mb] data was then fit to a monoexponential model of the form:

$$(2) \qquad [HHb+Mb]_{(t)} = [HHb+Mb]_{(b)} + A_{[HHb+Mb]} * (1 - e^{(t - TD_{[HHb+Mb]})/\tau_{[HHb+Mb]}})$$

Where $[HHb+Mb]_{(b)}$ is the mean [HHb+Mb] measured over the final 30 s of baseline cycling, $A_{[HHb]}$ is the asymptotic amplitude of the response, $TD_{[HHb+Mb]}$ is the time delay relative to the onset of exercise and $\tau_{[HHb+Mb]}$ is the time constant for the response. The model fitting window was constrained to $TD_{S\dot{C}V_{O2}}$. The amplitude of the [HHb+Mb] slow component was calculated by subtracting the average value of [HHb+Mb] during the final 30 s of exercise from the absolute [HHb+Mb] response (i.e. $[HHb+Mb]_{(b)} + A_{[HHb+Mb]}$). To indicate changes in muscle oxygenation and [THb+Mb] concentrations, the mean values for [HbO_2+MbO_2] and

[THb+Mb] were determined at baseline (30 s preceding each transition), at 30 s and 120 s into the exercise transition (15 s bin centred on 30 and 120 s), and at end exercise (final 30 s) to facilitate comparisons between conditions. These particular time points were chosen to allow comparisons between conditions early in the transition during the phase II increase in $\dot{V}O_2$ before the onset of the $\dot{V}O_2$ slow component and after the $\dot{V}O_2$ slow component had developed fully (i.e. at exercise termination).

Heart-rate kinetics were also modelled using a monoexponential function with the response constrained to the start of exercise (t = 0):

(3) $$HR_{(t)} = HR_{(b)} + A_{HR} * (1 - e^{(t / \tau_{HR})}$$

Where $HR_{(b)}$ is the mean HR measured over the final 30 s of baseline cycling, A_{HR} is the asymptotic amplitude of the response and τ_{HR} is the time constant of the response. The fitting window was constrained to $TD_{S\dot{C}V_{O2}}$.

Critical power and W' were estimated using three models: the hyperbolic power-time (P-T) model (Equation 4); the linear work-time (W-T) model, where the total work done is plotted against time (Equation 5); and the linear inverse-of-time (1/T) model (Equation 6), where power output is plotted against the inverse of time:

(4) $$P = W' / T + CP$$

(5) $$W = CP * T + W'$$

(6) $$P = W' * (1/T) + CP$$

The standard errors of the estimates (SEE) associated with CP and W' were expressed as a coefficient of variation (CV) relative to the parameter estimate. The model with the lowest average CV was then used for all subsequent analyses.

Statistical analyses. Two-way repeated measures analyses of variance (ANOVA, condition * work rate) were used to compare differences in all $\dot{V}O_2$, [HHb+Mb] and heart rate kinetic variables between tests. Three-way repeated measures ANOVAs (condition * work rate * time) were used to compare differences in blood [L^-], [HbO_2+MbO_2], and [THb+Mb] between tests. Planned repeated and simple contrasts were applied to identify the location of any significant main or interaction effects when found. Levene's test was used to check for equality of variances for independent groups and Mauchly's test was used to test for the assumption of sphericity for repeated measures factors. Paired samples t-tests were used to compare differences in critical power and W' between conditions. Where this assumption was violated, the Greenhouse-Geisser correction factor was applied to adjust the degrees of freedom. Pearson's product-moment correlation coefficient was used to explore the relationships between variables of interest. All data are presented as mean ± SD unless otherwise stated, with 95% confidence intervals presented for modelled time constant parameters. To highlight values for parameters measured across all four work rates, the overall mean across work rates ± SD is presented in text, with work rate-specific mean ± SD presented in tables. Independent samples t-tests were used to compare differences in $\tau_{\dot{V}O2}$ during heavy priming and severe exercise between groups. Statistical significance was accepted at $P < 0.05$.

RESULTS

Incremental ramp test. For the supine and upright group, $\dot{V}O_2$ max was 3.45 ± 0.48 l.min^{-1} (45.1 ± 5.2 ml.kg^{-1}.min^{-1}) and 4.05 ± 0.50 l.min^{-1} (51.8 ± 6.5 ml.kg^{-1}.min^{-1}), the GET was 1.94 ± 0.15 l.min^{-1} (111 ± 16 W) and 2.19 ± 0.32 l.min^{-1} (137 ± 24 W), respectively.

Priming exercise. Priming exercise was conducted at an average intensity of 172 ± 29 W (supine; 30 ± 5.1%Δ) and 214 ± 19 W (upright; 36 ± 2.0%Δ), and resulted in an elevated blood [L$^-$] immediately prior to the exhaustive constant work rate trials in both groups compared to control (*supine*: CON = 1.53 ± 0.38 vs. PRI = 4.14 ± 0.74 mmol.L^{-1}; *upright*: CON = 1.46 ± 0.46 vs. PRI = 3.67 ± 0.77 mmol.L^{-1}; both $P < 0.001$). There was no difference in end-exercise blood [L$^-$] between conditions in either group (*supine*: CON = 11.6 ± 2.1 vs. PRI = 12.4 ± 2.5 mmol.L^{-1}; *upright*: CON = 13.1 ± 3.0 vs. PRI = 13.3 ± 2.8 mmol.L^{-1}, both $P < 0.001$). $\tau_{\dot{V}O2}$ determined from the heavy-intensity bouts of priming exercise was greater in the supine group (44 ± 11 s, 95% CI 1.80 ± 0.87) when compared to the upright group (30 ± 10 s, 95% CI 1.55 ± 0.90 s; $P = 0.02$, table 1).

Oxygen uptake kinetics. The $\dot{V}O_2$ responses of a representative participant from each group at a single work rate in both conditions and their respective modelled fits are presented in figure 1. In the supine group, $\tau_{\dot{V}O2}$ was smaller in PRI compared to CON (CON = 54 ± 18 s, 95% CI 5.6 ± 3.5 s vs. PRI = 39 ± 11 s, 95% CI 3.5 ± 2.2 s; $P < 0.001$). $\tau_{\dot{V}O2}$ was not different between CON and PRI in the upright group (CON = 35 ± 8 s, 95% CI 4.4 ± 3.2 s vs. PRI = 37 ± 11 s, 95% CI 4.8 ± 3.8 s, $P = 0.82$, table 2). However, $A_{\dot{V}_{O_2}}$ was greater (CON = 2.38 ± 0.35 vs. PRI = 2.50 ± 0.28 l.min^{-1}; $P = 0.02$) and the magnitude of the slow component was smaller (CON = 0.44 ± 0.11 vs. PRI = 0.33 ± 0.11 l.min^{-1}; $P = 0.02$) in PRI compared to CON in the upright group (table 2).. The $\dot{V}O_2$ responses at each work rate and condition of a

representative participant from each group, along with the power-duration relationships in each condition, are shown in figure 2.

Power-duration relationship. The W-T model secured the lowest CV for each participant, and was thus used for all subsequent analyses. Critical power in PRI was greater than CON in the supine group (CON = 178 ± 31 W, CV 4 ± 2% vs. PRI = 185 ± 30 W, CV 2 ± 2% *P* = 0.006). There was no difference in critical power between CON and PRI in the upright group (CON = 236 ± 42 W, CV 3 ± 2% vs. PRI = 232 ± 35 W, CV 2 ± 1%; *P* = 0.57, figure 3). W' was not different between conditions in either group (*supine* CON = 16.4 ± 5 kJ, CV 17 ± 8 % vs. PRI = 15.9 ± 5.7 kJ, CV 12 ± 8%, *P* = 0.62; *upright* CON = 18.3 ± 4.6 kJ, CV 16 ± 7% vs. PRI = 17.7 ± 5.1 kJ, CV 15 ± 10%, *P* = 0.72). The $\tau_{\dot{V}O2}$ determined from the heavy-intensity priming exercise bouts that preceded the exhaustive constant work rate trials was significantly correlated with critical power (normalised to body mass and derived from the control condition) in the upright group (*r* = -0.80, *P* = 0.005). However, this relationship was not present in the supine group (*r* = 0.067, *P* = 0.86) (figure 4). The individual changes in W' between conditions in each participant in the upright group were inversely correlated with blood [L^-] immediately prior to the exhaustive constant work rate trials (*r* = -0.79, *P* = 0.007), whereas this relationship was not observed in the supine group (*r* = 0.27, *P* = 0.44).

NIRS parameters. In the supine group, $\tau_{[HHb+Mb]}$ was greater in PRI when compared to CON (CON = 8 ± 4 s, 95% CI 1.32 ± 0.80 s, vs. PRI = 12 ± 4 s, 95% CI 1.49 ± 0.88 s; *P* = 0.003). In the upright group, there was a trend for $\tau_{[HHb+Mb]}$ to be greater in PRI compared to CON (CON = 10 ± 5 s, 95% CI 1.31 ± 0.90 s, vs. PRI = 14 ± 10 s, 95% CI 2.0 ± 1.8 s; *P* = 0.10, table 3), whilst $A_{[HHb+Mb]}$ was also greater in PRI compared to CON (CON = 21 ± 3.6 vs. PRI = 24 ± 6.8 µM; *P* = 0.02, table 3) In the supine group, [HbO_2+MbO_2] was higher in PRI compared to CON (main

effect of condition, P = 0.04), however there was no effect of condition on [THb+Mb] (P = 0.11). In the upright group, [HbO_2+MbO_2] and [THb+Mb] were both elevated in PRI compared to CON (both P < 0.001) (figure 5).

Heart rate. τ_{HR} was reduced in PRI compared to CON in the supine group (CON = 52 ± 14 s, 95% CI 2.47 ± 0.82 s vs. PRI = 41 ± 7, 95% CI 1.96 ± 0.53 s; P = 0.006), whereas in the upright group, τ_{HR} was not different between CON and PRI (CON = 47 ± 13 s, 95% CI 2.83 ± 0.80 s vs. PRI = 49 ± 19, 95% CI 2.04 ± 0.96 s; P = 0.41). Baseline HR was greater in PRI than CON (CON = 89 ± 8 vs. PRI = 97 ± 13 beats.min^{-1}; P = 0.003) in the upright group.

DISCUSSION

The present study investigated the effects of priming exercise on critical power and $\dot{V}O_2$ kinetics during upright and supine exercise. We hypothesised that (i) priming exercise would reduce $\tau_{\dot{V}O2}$ in the supine but not the upright group, (ii) priming exercise would increase critical power in the supine but not the upright group, and (iii) critical power would be correlated with $\tau_{\dot{V}O2}$ in both body positions. Consistent with our first and second hypotheses, we found that when priming exercise was conducted in the supine position, $\tau_{\dot{V}O2}$ was reduced when compared to the control condition and this was accompanied by a concomitant increase in critical power. However, in the upright position there was no effect of priming exercise on either $\tau_{\dot{V}O2}$ or critical power. The present study therefore provides the first experimental evidence that $\tau_{\dot{V}O2}$ is an independent determinant of critical power. However, in contrast with our third hypothesis, the correlation between $\tau_{\dot{V}O2}$ and critical power that was apparent in the upright position was not evident in the supine position. Hence, an alternative interpretation is that the reduction in $\tau_{\dot{V}O2}$ is mechanistically related to the increase in critical power through shared physiological effects of priming exercise.

Consistent with the present findings, in the upright position Jones *et al.* (2003) and Burnley *et al.* (2011) have previously showed that priming exercise has no effect on critical power or $\tau_{\dot{V}O2}$. In contrast, Miura *et al.* (2009) demonstrated that priming exercise increased critical power in the upright position, though these authors did not model the $\dot{V}O_2$ responses to exercise. The discrepancy between the present data in the upright position and that of Miura *et al.* (2009) might be explained by the recruitment of participants with a higher aerobic fitness in the present study ($\dot{V}O_2$ max = ~52 vs. 42 ml.kg^{-1}.min^{-1} for the present study vs. Miura *et al.* 2009). Individuals with low aerobic fitness have slow $\dot{V}O_2$ kinetics that are readily speeded following priming exercise (Gurd *et al.* 2005; Scheuermann et al. 2002), whereas the same is not true for those with higher aerobic fitness (e.g. Burnley *et al.* 2000). A reduction of $\tau_{\dot{V}O2}$ following priming exercise might therefore account for the increased critical power demonstrated by Miura *et al.* (2009). Indeed, such an interpretation is consistent with our findings in the supine position in the present study, and thus the notion that $\tau_{\dot{V}O2}$ is mechanistically related to critical power.

Influence of priming exercise in the supine position.

In the absence of *a priori* information on the speed of $\dot{V}O_2$ kinetics during the fundamental phase, we utilised supine exercise as a means of slowing this phase in the control condition (Hughson *et al.* 1991; Jones *et al.* 2006; Koga *et al.* 1999; MacDonald *et al.* 1998), with an anticipated speeding occurring following priming exercise (Jones *et al.* 2006). Consequently, when $\tau_{\dot{V}O2}$ was determined at four severe power outputs in the supine position in the present study, the overall mean $\tau_{\dot{V}O2}$ (~54 s) was greater than the values observed in the present study in the upright group (overall mean = ~35 s). This finding has been attributed to a loss of the "hydrostatic gradient effect" of gravity in the supine position, thus lowering

the pressure head for blood-to-myocyte O_2 diffusion and limiting the rate of increase in $\dot{V}O_2$ at exercise onset (Koga *et al.* 1999).

In the present study following priming exercise, [HbO_2+MbO_2] was elevated and the $\tau_{[HHb+Mb]}$ was greater when compared to the control condition, indicating enhanced O_2 availability and a relatively greater increase in O_2 supply versus O_2 utilization at exercise onset. These effects presumably resulted from greater vasodilation and muscle blood flow at the onset of the criterion exercise bout (Gerbino *et al.* 1996; Hughson *et al.* 2003), and an improvement of the blood-myocyte O_2 diffusional gradient due to a right shift of the [HbO_2+MbO_2] curve, the latter due to a residual acidosis remaining from the initial exercise bout (Boning *et al.* 1991; Wasserman *et al.* 1991). Faster heart rate kinetics also likely contributed to greater O_2 availability in the exercising musculature by enabling a faster adjustment of convective O_2 delivery at exercise onset. Crucially, priming exercise in the supine position also resulted in a reduction in $\tau_{\dot{V}O2}$ (overall mean $\tau_{\dot{V}O2}$: ~54 vs. 39 s). The techniques employed in the present study cannot discriminate between faster mitochondrial $\dot{V}O_2$ kinetics (i.e. a reduction in metabolic inertia; Behnke *et al.* 2002) and the alleviation of an O_2 availability limitation, therefore we cannot exclude the possibility that the reduction of $\tau_{\dot{V}O2}$ observed herein was due to more rapid metabolic adjustments in overcoming metabolic inertia (Gurd *et al.* 2005). However, the present data are congruous with previous studies showing that increasing muscle O_2 supply in situations where O_2 availability is compromised is a primary mechanism by which $\tau_{\dot{V}O2}$ is reduced (DeLorey *et al.* 2004; Endo *et al.* 2005; Fukuba *et al.* 2004; Gurd *et al.* 2005; Hughson *et al.* 1993; Hughson & Inman, 1986; Koppo & Bouckaert, 2005; MacDonald *et al.* 2001; Perrey et al. 2003; Rossiter *et al.* 2001; Scheuermann *et al.* 2002). Regardless, the decreased $\tau_{\dot{V}O2}$ induced by priming exercise in the supine position

was observed alongside an increased critical power, suggesting that $\tau_{\dot{V}O2}$ is either an independent determinant of, or mechanistically related to, critical power.

Influence of priming exercise in the upright position.

In the upright position priming exercise appeared to enhance O_2 availability, as evidenced by increased [THb+Mb] and [HbO_2+MbO_2] immediately prior to and during the subsequent exercise; there was also some tendency for [HHb+Mb] kinetics to be slower. The increased amplitude of the heart rate response and elevated baseline heart rate following priming exercise compared to the control condition support this supposition. However, despite this evidence of increased O_2 availability, there was no impact of priming exercise on $\tau_{\dot{V}O2.}$ Rather, priming exercise resulted in an increased $\dot{V}O_2$ amplitude during the fundamental phase and a reduced $\dot{V}O_2$ slow component. These results are consistent with previous studies investigating the effects of priming exercise on $\dot{V}O_2$ kinetics in healthy young adults performing high-intensity upright cycle exercise. In such populations, $\tau_{\dot{V}O2}$ is insensitive to interventions which increase muscle O_2 supply and is limited principally by a metabolic inertia (Bearden & Moffatt, 2001; Burnley *et al.* 2000; 2001; 2002*a*; 2002*b*; 2005; 2006; Endo *et al.* 2005; Grassi *et al.* 1998; Jones *et al.* 2006; Koppo & Bouckaert, 2002; Perrey *et al.* 2003; Poole *et al.* 2008; Poole & Jones, 2012; Rossiter *et al.* 2002; Sahlin *et al.* 2005; Scheuermann *et al.* 2001; Wilkerson *et al.* 2004; Wilkerson *et al.* 2006; Wilkerson *et al.* 2005).

However, it has been shown that heavy-intensity priming exercise can reduce the $\tau_{\dot{V}O2}$ during moderate intensity exercise, particularly in those individuals with $\tau_{\dot{V}O2}$ values ≥ 30 s

(Gurd *et al.* 2005). Given the average values of $\tau_{\dot{V}O2}$ in the upright group in the present study (i.e. ~35 s); it is perhaps therefore surprising that priming exercise did not reduce $\tau_{\dot{V}O2.}$ However, the value of $\tau_{\dot{V}O2}$ increases with increasing exercise intensity, an effect demonstrable across (Jones *et al.* 2002; Koppo *et al.* 2004; Paterson & Whipp, 1991) and within (Spencer *et al.* 2011) exercise intensity domains. Indeed, we observed a smaller $\tau_{\dot{V}O2}$ (~30 s) during the heavy intensity priming bouts compared to severe intensity exercise, in the present study. Hence, it is likely that our participants would have demonstrated faster $\dot{V}O_2$ kinetics during moderate intensity exercise, with $\tau_{\dot{V}O2}$ values comparable to those typically seen in young, healthy individuals (i.e. 20-30 s) that are relatively insensitive to priming exercise (Gurd *et al.* 2005). The increased $\tau_{\dot{V}O2}$ with higher exercise intensities is likely due to the preferential recruitment of type II fibres, which possess inherently slower $\dot{V}O_2$ kinetics compared to type I fibres (Crow & Kushmerick, 1982; Reggiani *et al.* 1997; Willis & Jackman, 1994). Hence, in the present study the finding of relatively slower phase II $\dot{V}O_2$ kinetics in the upright severe intensity exercise bouts, which are not speeded by priming exercise, is consistent with the scientific literature.

Despite the impact of priming exercise on the physiological responses to subsequent exercise, in the upright group priming exercise had no impact on W' or the critical power in the upright group, and consequently exercise tolerance at any work rate. This is surprising when considering that previous studies have shown that prior heavy intensity exercise enhances the W' with no change in CP (Burnley *et al.* 2011; Jones *et al.* 2003). We therefore elected to perform priming exercise at a heavy intensity (estimated *a priori* as 40%Δ) to optimize any effects on exercise tolerance. However, Bailey *et al.* (2009) also demonstrated that prior heavy exercise had no impact on severe intensity exercise tolerance, despite a

greater fundamental $\dot{V}O_2$ amplitude and blunted $\dot{V}O_2$ slow component. Taken together, these results suggest that faster overall $\dot{V}O_2$ kinetics (as indicated by a greater fundamental $\dot{V}O_2$ amplitude and reduced slow component) may not determine the tolerable duration of exercise *per se*, but do so through interaction with other physiological parameters (Burnley & Jones, 2007). Indeed, we also observed a strong inverse correlation (r = -0.78) between blood [L^-] elevation prior to exercise and the change in W' (normalised to body mass) following priming. In the present study therefore, it appears that priming exercise was most effective at improving exercise tolerance in a given participant (via increasing W') when priming exercise was conducted in the lower regions of the heavy domain. However, in participants where the intensity of priming exercise approached critical power, W' tended to decrease or remain unchanged. It is possible that when priming exercise was conducted in closer proximity to critical power, the fatigue-related metabolite concentration of the muscle remained elevated prior to subsequent exercise, accounting for why there was no change in performance for these individuals. The reasons for the discrepancies between the present results and those presented previously (Bailey *et al.* 2009; Burnley *et al.* 2011; Jones *et al.* 2006) are unclear. However, despite many attempts, the optimal intensity for priming exercise has yet to be elucidated and likely depends on a variety of factors such as subject characteristics, the balance between the relative intensity of priming exercise and the duration of the intervening recovery period.

$\tau_{\dot{V}O2}$-critical power relation during upright and supine exercise.

Our first and second hypotheses were based in part on the findings of Murgatroyd et al. (2011), who observed a strong inverse relationship between $\tau_{\dot{V}O2}$ and critical power (r = -0.95). In repeating this analysis, we averaged together the four identical exercise transitions

used for priming exercise to increase the confidence in the $\dot{V}O_2$ kinetic parameters. This resulted in highly confident estimates of the $\tau_{\dot{V}O2}$, with 95% confidence intervals of 1.8 and 1.6 s for upright and supine exercise, respectively. Similarly to Murgatroyd *et al.* (2011), we observed a strong inverse relationship between the $\tau_{\dot{V}O2}$ and critical power (normalised to body mass) in the upright group (r = -0.80). However, in contrast to our third hypothesis, and despite our findings of a reduced $\tau_{\dot{V}O2}$ and increased critical power following priming exercise in the supine position, we observed no relationship between the $\tau_{\dot{V}O2}$ and critical power during supine exercise (r = 0.067). This may have been due to a kinetic distortion in the relationship between muscle and pulmonary $\dot{V}O_2$ induced by lower resting muscle perfusion in the supine position (Benson *et al.*2013); consequently, the relationship between $\tau_{\dot{V}O2}$ and critical power was obscured. Alternatively, it is possible that the determinants of critical power were modified in response to a change in body position.

Since the $\tau_{\dot{V}O2}$ determines the magnitude of the O_2 deficit at any given work rate, Murgatroyd *et al.* (2011) interpreted the strong $\tau_{\dot{V}O2}$-critical power relationship to suggest that $\tau_{\dot{V}O2}$ determines the upper work rate limit for which O_2 deficit accumulation can be stabilised and a steady-state attained, otherwise known as critical power. The reduction in $\tau_{\dot{V}O2}$ and increased critical power following priming exercise in the supine position in the present study are the first direct evidence in support of this hypothesis. However, the lack of a relationship between $\tau_{\dot{V}O2}$ and critical power in the supine position runs counter to this. Indeed, two recent studies by Broxterman *et al.* (2014; 2015) demonstrated that critical power is dependent on blood flow and thus O_2 delivery to the exercising musculature, consistent with the finding of increased critical power and enhanced muscle O_2 availability with priming exercise in the supine position in the present study. Notwithstanding that O_2

delivery is an important determinant of $\tau_{\dot{V}O2}$, the relative contribution of $\tau_{\dot{V}O2}$ and O_2 delivery in determining critical power may therefore be dependent on the exercising body position, or perhaps more accurately, the presence or absence of an O_2 delivery limitation. Type II muscle fibres are heavily recruited on transition from rest to high-intensity exercise (Krustrup *et al.* 2004; 2009). These muscle fibres operate at a lower microvascular O_2 pressure (PO_2mv) during contractions (McDonough et al. 2005), which is likely to be exacerbated in the supine position due to the loss of the hydrostatic gradient, with the subsequent impaired blood-to-myocyte flux and lowered intramyocyte PO_2 a likely cause of the slower $\dot{V}O_2$ kinetics. Importantly, these fibre types appear to be particularly sensitive to interventions aimed at increasing oxygen availability, and thus PO_2mv, such as dietary nitrate supplementation (Ferguson *et al.* 2015) and exercise training (Hirai *et al.* 2015). Hence the improvements in microvascular oxygen delivery afforded by priming exercise in the present study, as indicated by the NIRS data, and the consequent reductions in $\tau_{\dot{V}O2}$ may have been primarily due to effects on type II muscle fibres.

A higher PO_2mv following priming exercise in muscle regions comprised mainly of fast-twitch fibres would also be expected to slow the fall in intramyocyte PO_2 and thus abate the intracellular metabolic perturbations during high-intensity exercise (Δ[PCr], Δ[Cr], Δ[ADP]) and accumulation of [Pi], [K^+] and [H^+], which are implicated in the fatigue process (Allen, Lamb, & Westerblad, 2008; Grassi *et al.* 2011). Hence, in the supine position, priming exercise may raise critical power by virtue of an increase in the highest metabolic rate for which a steady-state of intramyocyte PO_2 can be achieved. Consistent with this interpretation is the enhancement of critical power in hyperoxia (Vanhatalo *et al.* 2010) and the inverse relationship between the proportion of type II muscle fibres and critical power

(Vanhatalo *et al.* 2016). The lack of a correlation between $\tau_{\dot{V}O2}$ and critical power in the supine group in the present study, yet both being improved following priming exercise, may therefore be explained by these parameters sharing physiological determinants (likely related to increased O_2 availability) that were upregulated following priming exercise. Hence in situations where O_2 delivery is normally compromised therefore (such as during exercise in the supine position), O_2 delivery may be the major limiting factor in determining critical power. Improvements to O_2 delivery, such as following priming exercise, may thus enhance critical power and reduce $\tau_{\dot{V}O2}$ without any dependence of critical power on $\tau_{\dot{V}O2}$ *per se*. However, in situations where O_2 delivery to the exercising musculature is adequate to meet the demand for ATP resynthesis (such as during upright cycle exercise in healthy adult humans) $\tau_{\dot{V}O2}$ may determine critical power over and above that of O_2 delivery. In such cases, $\tau_{\dot{V}O2}$ dictates the magnitude of reliance on substrate-level phosphorylation and depletion of O_2 stores contributing to energy metabolism during the rest-exercise transition (Whipp *et al.* 1982), and therefore the highest power at which the O_2 deficit can be stabilised.

There is considerable spatial heterogeneity in muscle deoxygenation during exercise (Koga *et al.* 2007), which is reduced following priming exercise (Saitoh *et al.* 2009; Prieur *et al.* 2010). A more homogenous distribution of blood flow, or rather a more appropriate matching of O_2 delivery to local metabolic rate ($\dot{Q}O_2/\dot{V}O_2$ ratio) may also have contributed to the decreased $\tau_{\dot{V}O2}$ following priming in the supine group in the present study. Furthermore, a priming-induced enhancement in the $\dot{Q}O_2/\dot{V}O_2$ ratio may also have mitigated the requirement for the recruitment of additional higher-order motor units to sustain power production, thus raising critical power. Hence, in addition to an improved

PO_2*mv*, an alternative mechanism by which priming exercise may have resulted in the independent improvement of $\tau_{\dot{V}O2}$ and critical power in the supine position is via a reduced heterogeneity of muscle deoxygenation. Such a hypothesis remains to be tested; however, previous research has indicated no relationship between the change in muscle deoxygenation heterogeneity and the slow component of pulmonary $\dot{V}O_2$ kinetics with priming exercise (Saitoh *et al.* 2009; Fukuoka *et al.* 2015).

Limitations.

Because the number of visits that participants were required to perform was already high, we were unable to repeat each experimental trial to enhance the signal-to-noise ratio of the $\dot{V}O_2$ responses. Repeated transitions at each intensity would have increased the number of visits from 9 to 17, placing undue requirements on the participants and increasing the risk of a training effect confounding the results. Despite this, the 95% confidence interval associated with the $\tau_{\dot{V}O2}$ was ~5 s; equal to the suggested minimally important difference to determine significant changes in $\tau_{\dot{V}O2}$ during interventional studies (Benson *et al.* 2017), and was smaller than the mean difference in $\tau_{\dot{V}O2}$ at all four work rates in the supine group. These confidence intervals were aided by the high amplitude of the individual $\dot{V}O_2$ responses, thus increasing the signal-to-noise ratio in each transition. Hence despite the use of single transitions at each work rate, we are confident that our reported effects of priming exercise on $\tau_{\dot{V}O2}$ following priming exercise in the supine and upright groups, respectively. Additionally, for reasons outlined above we were unable to perform additional trials if the errors associated with the parameters of the power-duration relationship were large. Whilst this resulted in the mean CV across groups and conditions for W' being ~15%, which is larger

than is typically reported in the literature, the CV surrounding critical power was typically very low (~3%), therefore we are confident in the differential effects of priming exercise on critical power between body positions.

Conclusions.

In conclusion, this study provides the first experimental evidence to show that $\tau_{\dot{V}O2}$ is mechanistically related to critical power. Specifically, when priming exercise was conducted in the supine position, $\tau_{\dot{V}O2}$ was significantly decreased and critical power was increased, whereas during upright exercise, $\tau_{\dot{V}O2}$ and critical power were both unaffected by priming exercise. During supine exercise, we also observed faster heart rate kinetics, slower [HHb+Mb] kinetics and increased [HbO_2+MbO_2] following priming exercise, suggesting that the changes in $\tau_{\dot{V}O2}$ and critical power arose through the enhanced muscle O_2 availability that attended priming exercise. However, the strong correlation observed herein between $\tau_{\dot{V}O2}$ and critical power for upright exercise was not apparent in the supine position, suggesting that other physiological factors, such as O_2 delivery, might determine critical power during supine exercise, with the concomitant improvement in $\tau_{\dot{V}O2}$ and critical power being an artefact of other shared physiological determinants.

REFERENCES

Allen DG, Lamb GD & Westerblad H (2008). Skeletal muscle fatigue: Cellular mechanisms. Physiol Rev 88, 387-332.

Bailey SJ, Vanhatalo A, Wilkerson DP, DiMenna FJ & Jones AM (2009). Optimizing the "priming" effect: influence of prior exercise intensity and recovery duration on O_2 uptake kinetics and severe-intensity exercise tolerance. J Appl Physiol 107, 1743-1756.

Barker T, Poole DC, Noble MI & Barstow TJ (2006). Human critical power-oxygen uptake relationship at different pedalling frequencies. Exp Physiol 91, 621-632.

Bearden SE & Moffatt RJ (2001). $\dot{V}O_2$ and heart rate kinetics in cycling: transitions from an elevated baseline. J Appl Physiol 90, 2081-2087.

Behnke BJ, Kindig CA, Musch TI, Sexton WL & Poole DC (2002). Effects of prior contractions on muscle microvascular oxygen pressure at the onset of subsequent contractions. J Physiol, 539, 927-934.

Belardinelli R, Georgiou D, Cianci G & Purcaro A (1999). Randomized, controlled trial of long-term moderate exercise training in chronic heart failure effects on functional capacity, quality of life, and clinical outcome. Circulation 99, 1173-1182.

Benson AP, Bowen ST, Ferguson C, Murgatroyd SR & Rossiter HB (2017). Data collection, handling and fitting strategies to optimize accuracy and precision of oxygen uptake kinetics estimation from breath-by-breath measurements. J Appl Physiol; DOI: 10.1152/japplphysiol.00988.2016.

Benson AP, Grassi B & Rossiter HB (2013). A validated model of oxygen uptake and circulatory dynamic interactions at exercise onset in humans. J Appl Physiol 115, 743-755.

Billat VI, Mousiel E, Roblot N & Melki J (2005). Inter- and intra-strain variation in mouse critical running speed. J Appl Physiol 98, 1258-1263.

Boning D, Hollnagel C, Boecker A & Goke S (1991). Bohr shift by lactic acid and the supply of O_2 supply to skeletal muscle. Respir Physiol 85, 231-243.

Boone J, Koppo K & Bouckaert J (2008). The $\dot{V}O_2$ response to submaximal ramp cycle exercise: Influence of ramp slope and training status. Resp Physiol Neurobiol 161, 291-297.

Broxterman RM, Ade CJ, Wilcox SL, Schlup SJ, Craig JC & Barstow TJ (2014). Influence of the duty cycle on the power-duration relationship: Observations and potential mechanisms. Resp Physiol Neurobiol 192, 102-111.

Broxterman RM, Ade CJ, Craig JC, Wilcox SL, Schlup SJ & Barstow TJ (2015). Influence of blood flow occlusion on muscle oxygenation characteristics and the parameters of the power-duration relationship. J Appl Physiol 118, 880-889.

Burnley M, Doust JH, Ball D & Jones AM (2002*a*). Effects of prior heavy exercise on $\dot{V}O_2$ kinetics during heavy exercise are related to changes in muscle activity. J Appl Physiol 93, 167-174.

Burnley M, Doust JH, Carter H & Jones AM (2001). Effects of prior exercise and recovery duration on oxygen uptake kinetics during heavy exercise in humans. Exp Physiol 86, 417-425.

Burnley M, Doust JH & Jones AM (2002*b*). Effects of prior heavy exercise, prior sprint exercise and passive warming on oxygen uptake kinetics during heavy exercise in humans. Eur J Appl Physiol 87, 424-432.

Burnley M, Doust JH & Jones AM (2005). Effects of prior warm-up regime on severe-intensity cycling performance. Med Sci Sports Exerc 37, 838-845.

Burnley M, Doust JH & Jones AM (2006). Time required for the restoration of normal heavy exercise $\dot{V}O_2$ kinetics following prior heavy exercise. J Appl Physiol 101, 1320-1327.

Burnley M, Davison G & Baker JR (2011). Effects of priming exercise on $\dot{V}O_2$ kinetics and the power-duration relationship. Med Sci Sports Exerc 43, 2171-2179.

Burnley M & Jones AM (2007). Oxygen uptake kinetics as a determinant of sports performance. Eur J Sports Sci 7, 63-79.

Burnley M, Jones AM, Carter H & Doust JH (2000). Effect of prior heavy exercise on phase II pulmonary oxygen uptake kinetics during heavy exercise. J Appl Physiol 89, 1387-1396.

Carter H, Jones, AM, Barstow TJ, Burnley M, Williams C & Doust JH (2000). Effect of endurance training on oxygen uptake kinetics during treadmill running. J Appl Physiol 89, 1744-1752.

Chidnok W, DiMenna FJ, Bailey SJ, Burnley M, Wilkerson DP, Vanhatalo A & Jones AM (2013*a*). $\dot{V}O_2$ max is not altered by self-pacing during incremental exercise. Eur J Appl Physiol 113, 529-539.

Chidnok W, Fulford J, Bailey SJ, DiMenna FJ, Skiba FJ, Vanhatalo A & Jones AM (2013*b*). Muscle metabolic determinants of exercise tolerance following exhaustion: relationship to the “critical power”. J Appl Physiol 115, 243-250.

Coats EM, Rossiter HB, Day JR, Miura A, Fukuba Y & Whipp BJ (2003). Intensity-dependent tolerance to exercise after attaining $\dot{V}O_2$ max in humans. J Appl Physiol 95, 483-490.

Copp SW, Hirai DM, Musch TI & Poole DC (2010). Critical speed in the rat: implications for hindlimb muscle blood flow distribution and fibre recruitment. J Physiol 588, 5077-5087.

Crow MT & Kushmerick MJ (1982). Phosphorylation of myosin light chains in mouse fast-twitch muscle associated with reduced actomyosin turnover rate. Science 217, 835-837.

De Blasi RA, Quaglia E & Ferrari M (1991). Skeletal muscle deoxygenation monitoring by near-infrared spectroscopy. Biochem Int 25, 241-248.

De Blasi RA, Cope M, Elwell C, Safoue F & Ferrari M (1993). Noninvasive measurement of human forearm oxygen consumption by near infrared spectroscopy. Eur J Appl Physiol 67, 20-25.

DeLorey DS, Jowalchuk JM & Paterson DH (2003). Relationship between pulmonary O_2 uptake kinetics and muscle deoxygenation during moderate-intensity exercise. J Appl Physiol 95, 113-120.

DeLorey DS, Kowalchuk JM & Paterson DH (2004). Effects of prior heavy-intensity exercise on pulmonary O_2 uptake and muscle deoxygenation kinetics in young and older adult humans. J Appl Physiol 97, 998-1004.

Endo M, Okada Y, Rossiter HB, Ooue A, Miura A, Koga S & Fukuba Y (2005). Kinetics of pulmonary $\dot{V}O_2$ and femoral artery blood flow during repeated bouts of heavy exercise. Eur J Appl Physiol 95, 418-430.

Ferguson SK, Holdsworth CT, Wright JL, Fees AJ, Allen JD, Jones AM, Musch TI & Poole DC (2015). Microvascular oxygen pressures in muscles comprised of different fibre types: Impact of dietary nitrate supplementation. Nitric Oxide 48, 38-43.

Ferrari M, Binzoni T & Quaresima V (1997). Oxidative metabolism in muscle. Phil Trans R Soc B 352, 677-683.

Ferreira LF, Lutjemeier BJ, Townsend DK & Barstow TJ (2006). Effects of pedal frequency on estimated muscle microvascular O_2 extraction. J Appl Physiol 96, 558-563.

Fukuba Y, Ohe Y, Miura A, Kitano A, Endo M, Sato H, Miyachi M, Koga S & Fukuda O (2004). Dissociation between time courses of femoral artery blood flow and pulmonary $\dot{V}O_2$ during repeated bouts of knee extension exercise in humans. Exp Physiol 89, 243-253.

Fukuoka Y, Poole DC, Barstow TJ, Kondo N, Nishiwaki M, Okushima D & Koga S (2015). Reduction of $\dot{V}O_2$ slow component by priming exercise: mechanistic insights from time-resolved near-infrared spectroscopy. Physiol Rep 3; DOI: 10.14814/phy2.12432.

Gaesser GA & Wilson IA (1988). Effects of continuous and interval training on parameters of the power-endurance time relationship for high-intensity exercise. Int J Sports Med 9, 417-421.

Gerbino A, Ward SA & Whipp BJ (1996). Effects of prior exercise on pulmonary gas-exchange kinetics during high-intensity exercise in humans. J Appl Physiol 80, 99-107.

Grassi B, Gladden LB, Stary CM, Wagner PD & Hogan MC (1998). Peripheral O_2 diffusion does not affect $\dot{V}O_2$ on kinetics in isolated in situ canine muscle. J Appl Physiol 85, 1404-1412.

Grassi B, Pogliaghi S, Rampichini S, Quaresima V, Ferrari M, Marconi C & Cerretelli P (2003). Muscle oxygenation and pulmonary gas exchange kinetics during cycling exercise on-transitions in humans. J Appl Physiol 95, 149-158.

Grassi B, Porcelli S, Salvadego D & Zoladz JA (2011). Slow $\dot{V}O_2$ kinetics during moderate intensity exercise as markers of lower metabolic stability and lower exercise tolerance. Eur J Appl Physiol 111, 345-355.

Gurd BJ, Scheuermann BW, Paterson DH & Kowalchuk JM (2005). Prior heavy-intensity exercise speeds $\dot{V}O_2$ kinetics during moderate-intensity exercise in young adults. J Appl Physiol 98, 1371-1378.

Hill DW (1993). The critical power concept. A review. Sports Med 16, 237-254.

Hirai DM, Musch TI & Poole DC (2015). Exercise training in chronic heart failure: improving skeletal muscle O_2 transport and utilization. Am J Physiol Heart Circ Physiol 309, 1419-1439.

Hughson RL, Cochrane JE & Butler GC (1993). Faster O_2 uptake kinetics at onset of supine exercise with than without lower body negative pressure. J Appl Physiol 75, 1962-1967.

Hughson RL & Inman MD (1986). Faster kinetics of $\dot{V}O_2$ during arm exercise with circulatory occlusion of the legs. Int J Sports Med 7, 22-25.

Hughson RL, Schijvens H, Burrows S, Devitt D, Betik AC & Hopman MTE (2003). Blood flow and metabolic control at the onset of heavy exercise. Int J Sport Health Sci 1, 1-9.

Hughson RL, Xing HC, Borkhoff C & Butler GC (1991). Kinetics of ventilation and gas exchange during supine and upright cycle exercise. Eur J Appl Physiol 63, 300-307.

Jenkins DG & Quigley BM (1992). Endurance training enhances critical power. Med Sci Sports Exerc 24, 1283-1289.

Jones AM & Carter H (2000). The effect of endurance training on parameters of aerobic fitness. Sports Med 29, 373-386.

Jones AM, Carter H, Pringle JS & Campbell IT (2002). Effect of creatine supplementation on oxygen uptake kinetics during submaximal cycle exercise. J Appl Physiol 92, 2571-2577.

Jones AM, Berger NJA, Wilkerson DP & Roberts CL (2006). Effects of "priming" exercise on pulmonary O_2 uptake and muscle deoxygenation kinetics during heavy-intensity cycle exercise in the supine and upright positions. J Appl Physiol 101, 1432-1441.

Jones AM, Wilkerson DP, Burnley M & Koppo K (2003). Prior heavy exercise enhances performance during subsequent perimaximal exercise. Med Sci Sports Exerc 35, 2085-2092.

Jones AM, Wilkerson DP, DiMenna F, Fulford J & Poole DC (2008). Muscle metabolic responses to exercise above and below the "critical power" assessed using ^{31}P-MRS. Am J Physiol Regul Integr Comp Physiol 294, 585-593.

Kaplan RM, Hartwell SL, Wilson DK & Wallace JP (1987). Effects of diet and exercise interventions on control and quality of life in non-insulin-dependent diabetes mellitus. J Gen Intern Med 2, 220-228.

Koppo K & Bouckaert J (2002). The decrease in $\dot{V}O_2$ slow component induced by prior exercise does not affect time to exhaustion. Int J Sports Med 23, 262-267.

Koppo K & Bouckaert J (2005). Prior arm exercise speeds the $\dot{V}O_2$ kinetics during arm exercise above the heart level. Med Sci Sports Exerc 37, 613-619.

Koppo K, Bouckaert J & Jones AM (2004). Effect of training status and exercise intensity on the on-transient $\dot{V}O_2$ kinetics. Med Sci Sports Exerc 36, 225-232.

Koga S, Poole DC, Ferreira LF, Whipp BJ, Kondo N, Saitoh T, Ohmae E & Barstow TJ (2007). Spatial heterogeneity of quadriceps muscle deoxygenation kinetics during cycle exercise. J Appl Physiol 103, 2049-2056.

Koga S, Shiojiri T, Shibasaki M, Kondo N, Fukuba Y & Barstow TJ (1999). Kinetics of oxygen uptake during supine and upright heavy exercise. J Appl Physiol 87, 253-260.

Krustrup P, Jones AM, Wilkerson DP, Calbet JAL & Bangsbo J (2009). Muscle and pulmonary O2 uptake kinetics during moderate- and high-intensity sub-maximal knee-extensor exercise in humans. J Physiol 587, 1843-1856.

Krustrup P, Söderlund K, Mohr M & Bangsbo J (2004). The slow component of oxygen uptake during intense sub-maximal exercise in man is associated with additional fibre recruitment. Pflugers Arch – Eur J Physiol 447, 855-866.

MacDonald MJ, Naylor HL, Tschakovsky ME & Hughson RL (2001). Peripheral circulatory factors limit rate of increase in muscle O_2 uptake at the onset of heavy exercise. J Appl Physiol 83, 1318-1325.

MacDonald MJ, Shoemaker JK, Tschakovsky ME & Hughson RL (1998). Alveolar oxygen uptake and femoral artery blood flow dynamics in upright and supine leg exercise in humans. J Appl Physiol 85, 1622-1628.

Marchionni N, Fattirolli F, Fumagalli S, Oldridge N, Del Lungo F, Morosi L, Burgisser C & Masotti G. Improved exercise tolerance and quality of life with cardiac rehabilitation of older patients after myocardial infarction results of a randomized, clinical trial. Circulation 107, 2201-2206.

Marwood S, Roche D, Rowland T, Garrard M & Unnithan VB (2010). Faster pulmonary oxygen uptake kinetics in trained versus untrained male adolescents. Med Sci Sports Exerc 42, 127-134.

McDonough P, Behnke BJ, Padilla DJ, Musch TI & Poole DC (2005). Control of microvascular oxygen pressures in rat muscles comprised of different fibre types. J Physiol 563, 903-913.

McNaughton L & Thomas D (1996). Effects of differing pedalling speeds on the power-duration relationship of high intensity cycle ergometry. Int J Sports Med 17, 287-292.

Miura A, Shiragiku C, Hirotoshi Y, Kitano A, Endo MY, Barstow TJ, Morton H & Fukuba Y (2009). The effect of prior heavy exercise on the parameters of the power-duration curve for cycle ergometry. Appl Physiol Nutr Metab 34, 1001-1007.

Monod H & Scherrer J (1965). The work capacity of a synergic muscle group. Ergonomics 8, 329-338.

Moritani T, Nagata A, Devries HA & Muro M (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics 24, 339-350.

Murgatroyd SR, Ferguson C, Ward SA, Whipp BJ & Rossiter HB (2011). Pulmonary O_2 uptake kinetics as a determinant of high-intensity exercise tolerance in humans. J Appl Physiol 110, 1598-1606.

Paterson & Whipp (1991). Asymmetries of oxygen uptake transients at the on- and offset of heavy exercise in humans. J Physiol 443, 575-586.

Perrey S, Scott J, Mourot L & Rouillon JD (2003). Cardiovascular and oxygen uptake kinetics during sequential heavy cycling exercises. Can J Appl Physiol 28, 283-298.

Poole DC, Barstow TJ, McDonough P & Jones AM (2008). Control of oxygen uptake during exercise. Med Sci Sports Exerc 40, 462-474.

Poole DC & Jones AM (2005). Oxygen uptake kinetics in sport, exercise and medicine. Routledge.

Poole DC & Jones AM (2012). Oxygen uptake kinetics. Compr Physiol 2, 933-996.

Poole DC & Jones AM (2017). Measurement of the maximum oxygen uptake $\dot{V}O_2$ max: $\dot{V}O_2$ peak is no longer acceptable. J Appl Physiol 122, 997-1002.

Poole DC, Ward SA, Gardner GW & Whipp BJ (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. Ergonomics 31, 1265-1279.

Prieur F, Berthoin S, Marles A, Blondel N & Mucci P (2010). Heterogeneity of muscle deoxygenation kinetics during two bouts of repeated heavy exercises. Eur J Appl Physiol 109, 1047-1057.

Reis LF, Guimarães FS, Fernandes SJ, Cantanhede LA, Dias CM, Lopes AJ & De Menezes SLS (2013). A long-term pulmonary rehabilitation program progressively improves exercise tolerance, quality of life and cardiovascular risk factors in patients with COPD. Eur J Phys Rehabil Med 49, 491-497.

Rossiter HB, Ward SA, Kowalchuk JM, Howe FA, Griffiths JR & Whipp BJ (2001). Effects of prior exercise on oxygen uptake and phosphocreatine kinetics during high-intensity knee-extension exercise in humans. J Physiol 537, 291-303.

Rossiter HB, Ward SA, Kowalchuk JM, Howe FA, Griffiths JR & Whipp BJ (2002). Dynamic asymmetry of phosphocreatine concentration and O_2 uptake between the on- and off-transients of moderate- and high-intensity exercise in humans. J Physiol 541, 991-1002.

Sahlin K, Sorensen JB, Gladden LB, Rossiter HB & Pedersen PK (2005). Prior heavy exercise eliminates $\dot{V}O_2$ slow component and reduces efficiency during submaximal exercise in humans. J Physiol 564, 765-773.

Saitoh T, Ferreira LF, Barstow TJ, Poole DC, Ooue A, Kondo N & Koga S (2009). Effects of prior heavy exercise on heterogeneity of muscle deoxygenation kinetics during subsequent heavy exercise. Am J Physiol Regul Integr Comp Physiol 297, 615-621.

Scheuermann BW, Hoelting BD, Noble ML & Barstow TJ (2001). The slow component of O_2 uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. J Physiol 531, 245-256.

Scheuermann BW, Bell C, Paterson DH, Barstow TJ & Kowalchuk JM (2002). Oxygen uptake kinetics for moderate exercise are speeded in older humans by prior heavy exercise. J Appl Physiol 92, 609-616.

Spencer MD, Murias JM, Kowalchuk JM & Paterson DH (2011). Pulmonary O_2uptake and muscle deoxygenation kinetics are slowed in the upper compared with lower region of the moderate-intensity exercise domain in older men. Eur J Appl Physiol 111, 2139-2148.

Vanhatalo A, Black MI, DiMenna FJ, Blackwell JR, Schmidt JF, Thompson C, Wylie LJ, Mohr M, Bangsbo J, Krustrup P & Jones AM (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationships to muscle fibre type. J Physiol 594, 4407-4423.

Vanhatalo A, Fulford J, DiMenna FJ & Jones AM (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a ^{31}P magnetic resonance spectroscopy study. Exp Physiol 95, 528-540.

Wasserman K, Hansen JE & Sue DY (1991). Facilitation of oxygen consumption by lactic acidosis during exercise. News Physiol Sci 6, 29-34.

Whipp BJ, Ward SA, Lamarra N, Davis JA & Wasserman K (1982). Parameters of ventilatory and gas exchange dynamics during exercise. J Appl Physiol 52, 1506-1513.

Whipp BJ & Ward SA (1990). Physiological determinants of pulmonary gas exchange kinetics during exercise. Med Sci Sports Exerc 22, 62-71.

Wilkerson DP, Koppo K, Barstow TJ & Jones AM (2004). Effects of prior multiple-sprint exercise on pulmonary O_2 uptake kinetics following the onset of perimaximal exercise. J Appl Physiol 97, 1227-1236.

Wilkerson, D. P., Rittweger, J., Berger, N. J. A., Naish, P. F. & Jones, A. M. 2005. Influence of recombinant human erythropoietin treatment on pulmonary O_2 uptake kinetics during exercise in humans. *J Physiol*, 568, 639-652.

Wilkerson, D. P., Berger, N. J. A. & Jones, A. M. 2006. Influence of hyperoxia on pulmonary O_2 uptake kinetics following the onset of exercise in humans. *Resp Physiol Neurobiol*, 153, 92-106.

Willis WT & Jackman MR (1994). Mitochondrial function during heavy exercise. Med Sci Sports Exerc 26, 1347-1353.

ADDITIONAL INFORMATION

The authors declare no conflicts of interest or sources of funding.

AUTHOR CONTRIBUTIONS

SM conceived the idea for the project. RPG, DMR, and SM contributed to the design of the protocol. RPG collected and analysed the data. RPG drafted the manuscript and DMR and SM revised it critically. All authors approved the final version of the manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

ACKNOWLEDGEMENTS

The authors would like to thank Marc Wells for his contributions to data collection and all participants for their efforts.

TABLES

Table 1. Pulmonary oxygen uptake kinetics during heavy-intensity priming exercise performed in the upright and supine positions.

	Upright		Supine		
	Mean	SD	Mean	SD	
$\dot{V}O_2$ baseline, l/min	0.97	0.13	0.82	0.09	*
$TD_{\dot{V}_{O2}}$, s	13	3	13	4	
$\tau_{\dot{V}O2}$, s	30	10	44	11	*
$A_{\dot{V}_{O2}}$, , l/min	1.70	0.24	1.46	0.25	*
Gain, ml.min^{-1}.W^{-1}	8.65	0.34	7.09	0.81	*
$SC_{\dot{V}_{O2}}$, , l/min	0.14	0.06	0.12	0.06	
End-ex $\dot{V}O_2$, l/min	2.82	0.35	2.40	0.28	*

$TD_{\dot{V}_{O2}}$, fundamental time delay; $\tau_{\dot{V}O2}$, fundamental time constant; $A_{\dot{V}_{O2}}$, fundamental amplitude; Gain,

increase in fundamental phase $\dot{V}O_2$ per unit increase in power output; $SC_{\dot{V}O2}$, , magnitude of the $\dot{V}O_2$ slow component; End-ex $\dot{V}O_2$, end-exercise $\dot{V}O_2$. * indicates significantly different from the upright group (*P*< 0.05).

Table 2. Pulmonary oxygen uptake responses to exercise with and without priming exercise.

	Supine				Upright			
Parameter	Control		Primed		Control		Primed	
$\dot{V}O_2$ baseline, l/min	Mean	SD	Mean	SD	Mean	SD	Mean	SD
WR 1	0.81	0.13	0.90	0.12	1.06	0.15	1.03	0.13
WR 2	0.89	0.09	0.86	0.05	1.04	0.17	1.07	0.09
WR 3	0.87	0.11	0.91	0.10	1.00	0.14	1.06	0.26
WR 4	0.86	0.13	0.88	0.11	1.07	0.22	1.00	0.16
$TD_{\dot{V}O2}$, s								
WR 1	12	6	12	9	8	8	9	6
WR 2	14	4	13	7	9	6	9	6
WR 3	9	6	13	6	9	9	7	9
WR 4	13	5	15	4	13	5	7	8
$\tau_{\dot{V}O2}$, s			*					
WR 1	59	18	38	13	40	8	42	14
WR 2	53	17	41	8	34	6	35	9
WR 3	57	21	44	12	37	8	34	13
WR 4	45	15	36	11	31	10	38	11
$A_{\dot{V}O2}$, l/min						*		
WR 1	1.9	0.4	1.82	0.32	2.20	0.39	2.35	0.31
WR 2	2.07	0.47	2.07	0.33	2.24	0.43	2.40	0.39
WR 3	2.23	0.34	2.26	0.33	2.58	0.46	2.47	0.39
WR 4	2.35	0.58	2.18	0.53	2.52	0.33	2.78	0.36
Gain, $ml.min^{-1}.W^{-1}$						*		
WR 1	9.10	0.92	9.00	0.47	8.66	0.48	9.49	0.74
WR 2	9.90	2.71	9.98	2.29	8.27	0.52	8.93	0.48
WR 3	9.18	1.13	9.33	0.99	8.70	0.89	8.26	0.92
WR 4	8.85	1.41	8.19	1.37	7.95	0.54	* 8.85	1.34
$SC_{\dot{V}O2}$, l/min								
WR 1	0.54	0.33	0.54	0.28	0.62	0.28	0.53	0.23
WR 2	0.39	0.34	0.37	0.23	0.64	0.38	0.43	0.26
WR 3	0.22	0.34	0.22	0.18	0.30	0.14	0.27	0.24
WR 4	0.01	0.39	0.20	0.35	0.16	0.19	0.10	0.19
End-ex $\dot{V}O_2$, l/min								
WR 1	3.15	0.51	3.26	0.37	3.87	0.69	3.89	0.53
WR 2	3.36	0.43	3.31	0.33	3.91	0.49	3.90	0.44
WR 3	3.29	0.41	3.39	0.38	3.87	0.47	3.81	0.48
WR 4	3.18	0.32	3.31	0.39	3.75	0.50	3.91	0.38

$TD_{\dot{V}_{O2}}$, fundamental time delay; $\tau_{\dot{V}O2}$, fundamental time constant; $A_{\dot{V}_{O2}}$, fundamental amplitude; Gain, increase in fundamental phase $\dot{V}O_2$ per unit increase in power output; $SC_{\dot{V}_{O2}}$, magnitude of the $\dot{V}O_2$ slow component; End-ex $\dot{V}O_2$, end-exercise $\dot{V}O_2$. * indicates significant main effect of condition ($P <$ 0.05).

Table 3. Muscle deoxygenation kinetic responses at each power output with and without priming exercise.

	Supine				Upright			
Parameter	Control		Primed		Control		Primed	
$[HHb+Mb]_{(b)}$, μM	Mean	SD	Mean	SD	Mean	SD	Mean	SD
WR 1	26.8	11.1	18.3	15.2	17.6	11.5	8.0	5.8
WR 2	14.0	7.0	14.4	14.8	19.7	25.4	12.8	11.5
WR 3	20.9	14.8	13.2	11.7	13.8	9.8	10.0	6.6
WR 4	17.7	13.5	15.1	9.8	12.1	8.2	13.9	16.4
$TD_{[HHb+Mb]}$, s								
WR 1	9	3	6	2	6	2	7	4
WR 2	7	3	5	5	7	2	6	2
WR 3	5	2	6	4	5	2	7	5
WR 4	6	3	6	3	7	3	6	3
$\tau_{[HHb+Mb]}$, s			*					
WR 1	8	2	12	7	12	6	18	11
WR 2	8	4	12	4	10	8	15	8
WR 3	9	5	11	3	12	12	12	11
WR 4	7	3	8	3	8	6	17	12
$A_{[HHb+Mb]}$, μM						*		
WR 1	21.3	14.8	24.9	18.9	19.4	16.1	15.8	12.6
WR 2	19.3	12.5	33.4	29.6	24.8	29.3	31.4	45.7
WR 3	24.9	17.6	32.8	29.1	18.6	21.0	26.8	20.4
WR 4	28.8	28.0	30.7	21.1	16.2	13.6	21.0	15.4
$SC_{[HHb+Mb]}$, μM								
WR 1	23.4	13.4	10.8	17.3	12.5	10.5	7.8	10.9
WR 2	19.0	17.1	11.2	9.0	11.4	18.6	4.2	4.7
WR 3	8.7	7.3	7.1	15.1	3.6	5.3	6.7	8.3
WR 4	1.8	9.4	2.0	3.0	1.3	3.3	2.1	7.0

$[HHb+Mb]_{(b)}$, mean [HHb+Mb] over last 30 s of baseline; $TD_{[HHb+Mb]}$, time delay before exponential rise in [HHb+Mb]; $\tau_{[HHb+Mb]}$, time constant of [HHb+Mb] response; $A_{[HHb+Mb]}$, amplitude of [HHb+Mb] response; $SC_{[HHb+Mb]}$, magnitude of the [HHb+Mb] slow component. * indicates significant main effect of condition ($P < 0.05$).

FIGURE LEGENDS

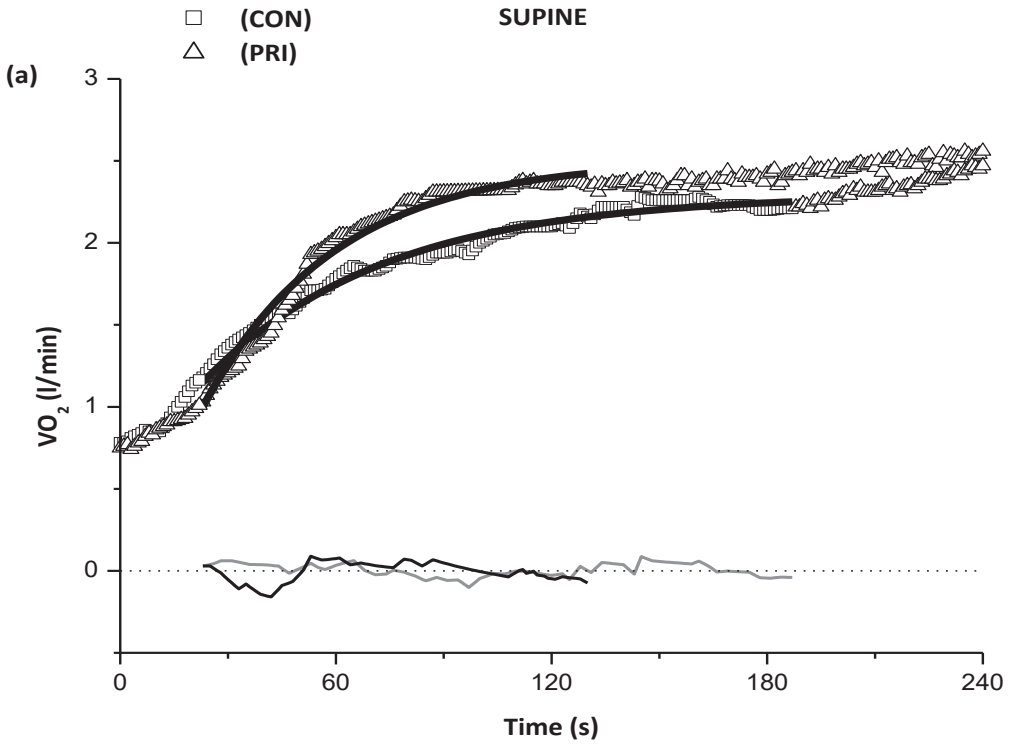
Fig. 1. $\dot{V}O_2$ responses and best-fit modelled responses of a representative participant from the supine (a) and upright (b) groups at a representative work rate. Open squares = CON (with grey line of residuals) and open triangles = PRI (with black line of residuals). Solid black lines represent modelled fits for both groups.

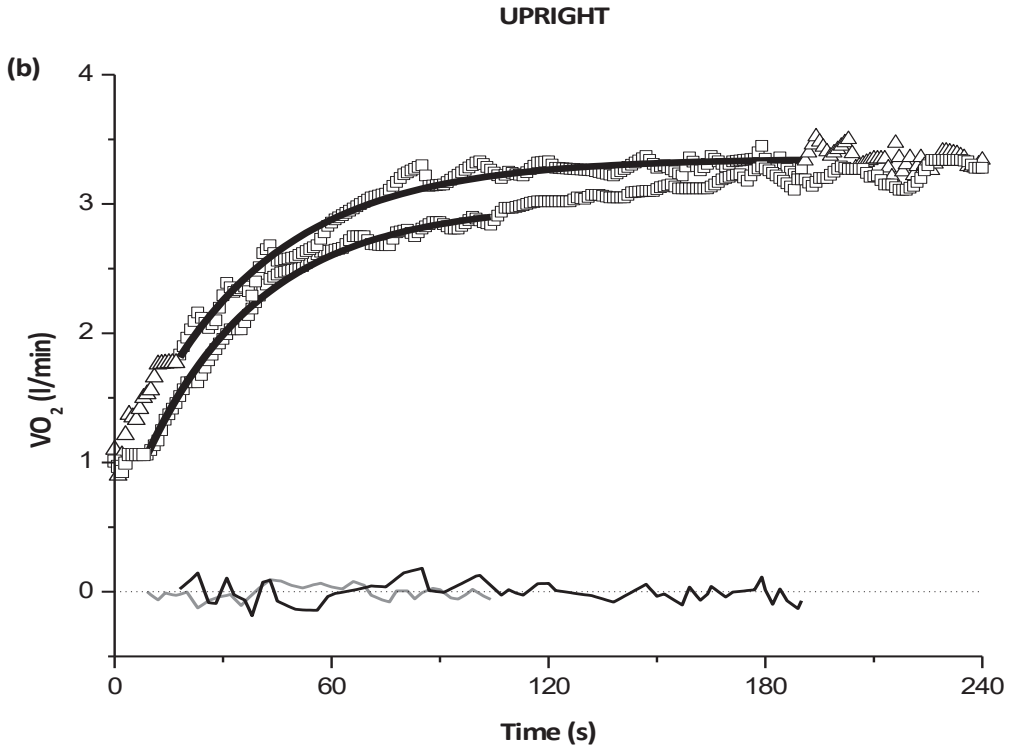
Fig. 2. $\dot{V}O_2$ responses and power-duration relationships with and without priming exercise in the supine (panels *a, b,* and *c*; participant 1) and upright (panels *d, e,* and *f*; participant 9) in two representative participants. *a & d,* $\dot{V}O_2$ responses in the control condition in supine and upright positions, respectively. *b & e,* $\dot{V}O_2$ responses in the primed condition in supine and upright positions, respectively. WR 1 = *black circles;* WR 2 = *white circles*; WR 3 = *black triangles*; WR 4 = *white triangles*. The *dashed horizontal lines* represent the participant's $\dot{V}O_2$ max whereas the *dotted vertical lines* allow comparison of time to exhaustion between conditions. *c & f*, power-duration relationships in both conditions in supine and upright positions, respectively. Control = *white circles,* primed = *black triangles.*

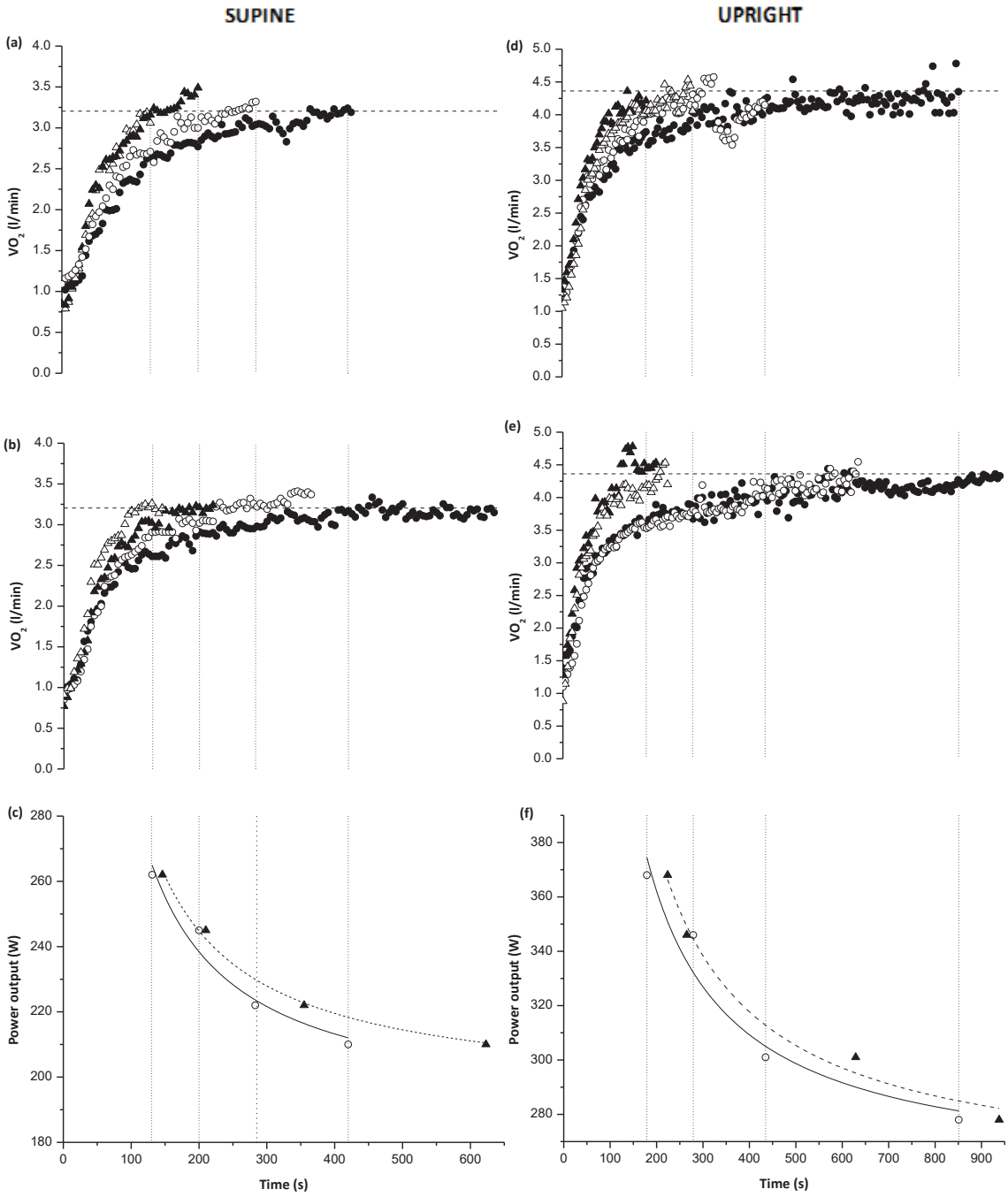
Fig. 3**.** The group mean ± SD critical power measured in the control (CON) and primed (PRI) conditions in the supine (panel A) and upright (panel B) groups. The critical power group means ± SD are shown as open bars and individual participant changes in critical power between conditions are shown as dashed black lines. * represents a significant difference between conditions (*P* = 0.006).

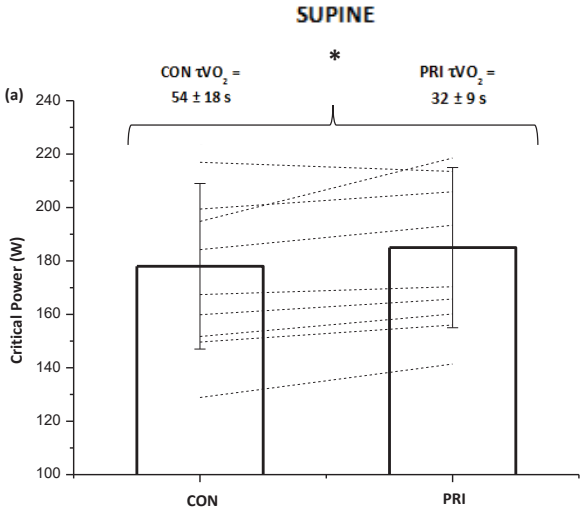
Fig. 4. Correlations between critical power normalised to body mass and the $\tau_{\dot{V}O2}$ for the supine (a) and upright (b) groups. Pearson's correlation coefficient values (*r*) are also displayed. The correlation shown in panel *b* was significant (*P* = 0.05).

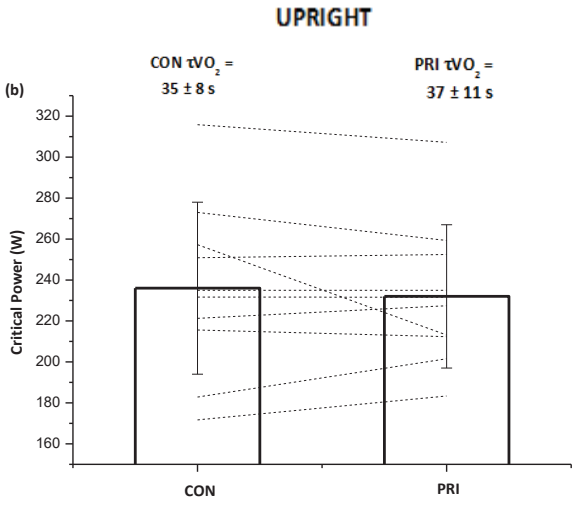
Fig. 5. Comparisons of group means ± SD across all work rates for oxyhaemoglobin ([HbO_2+MbO_2]) and total haemoglobin ([THb+Mb]) in both groups. *a* and *b*, [HbO_2+MbO_2] and [THb+Mb] responses in the supine group, respectively. *c* and *d*, [HbO_2+MbO_2] and [THb+Mb] responses in the upright group, respectively. Control = *white circles,* primed = *black triangles.* * represents a significant main effect of condition

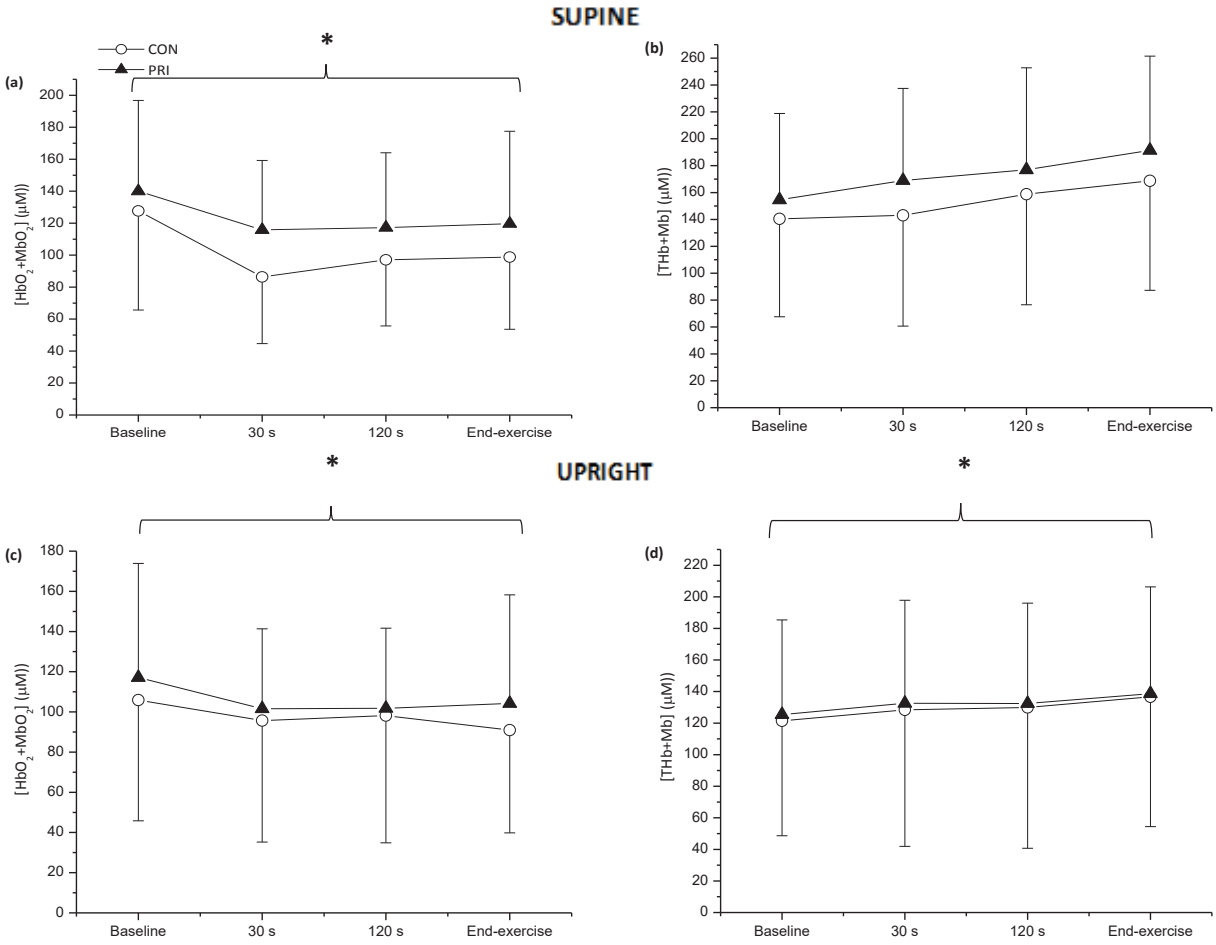

(CON)
(PRI)
SUPINE
(a)
3
2
1
0
VO2 (l/min)
0
60
120
180
240
Time (s)

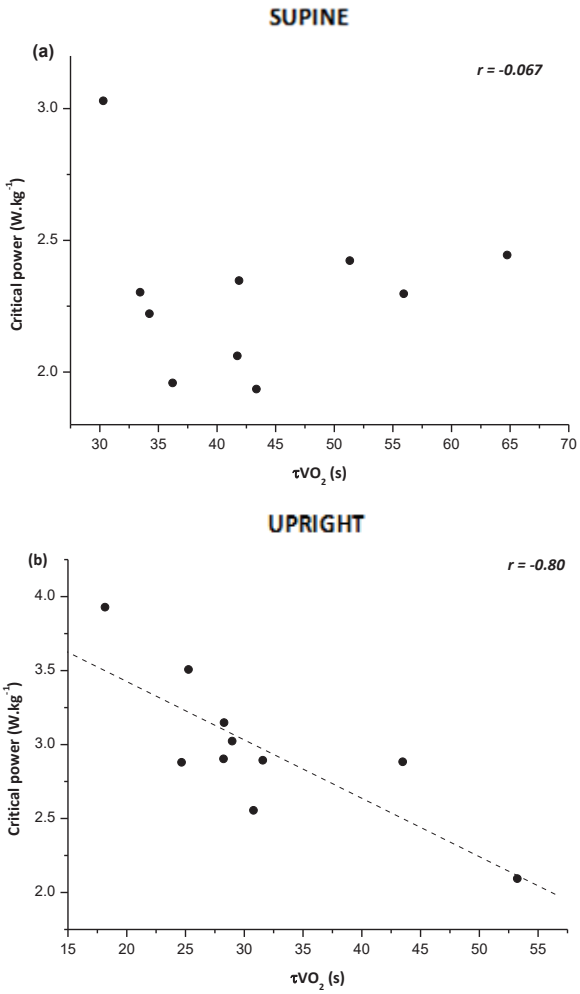

UPRIGHT
(b)
4
3
2
1
0
VO2 (l/min)
0
60
120
180
240
Time (s)


SUPINE
UPRIGHT
(a)
(b)
(c)
(d)
(e)
(f)
VO2 (l/min)
Power output (W)
Time (s)


SUPINE
*
CON τVO2 =
54 ± 18 s
PRI τVO2 =
32 ± 9 s
(a)
Critical Power (W)
240
220
200
180
160
140
120
100
CON
PRI


UPRIGHT
CON τVO2 =
35 ± 8 s
PRI τVO2 =
37 ± 11 s
(b)
Critical Power (W)
320
300
280
260
240
220
200
180
160
CON
PRI


SUPINE
UPRIGHT
(a)
(b)
(c)
(d)
CON
PRI
*
[HbO2+MbO2] (μM))
[THb+Mb] (μM))
Baseline
30 s
120 s
End-exercise


SUPINE
(a)
r = -0.067
Critical power (W.kg-1)
3.0
2.5
2.0
30
35
40
45
50
55
60
65
70
τVO2 (s)
UPRIGHT
(b)
r = -0.80
Critical power (W.kg-1)
4.0
3.5
3.0
2.5
2.0
15
20
25
30
35
40
45
50
55
τVO2 (s)