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ORIGINAL ARTICLE

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Effects of prior heavy exercise, prior sprint exercise and passive warming on oxygen uptake kinetics during heavy exercise in humans

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Abstract Prior heavy exercise (above the lactate threshold, Th_{la}) increases the amplitude of the primary oxygen uptake ($\dot{V}\dot{V}O_2$) response and reduces the amplitude of the $\dot{V}O_2$ slow component during subsequent heavy exercise. The purpose of this study was to determine whether these effects required the prior performance of an identical bout of heavy exercise, or if prior short-duration sprint exercise could cause similar effects. A secondary purpose of this study was to determine the effect of elevating muscle temperature (through passive warming) on $\dot{V}O_2$ kinetics during heavy exercise. Nine male subjects performed a 6-min bout of heavy exercise on a cycle ergometer 6 min after: (1) an identical bout of heavy exercise; (2) a 30-s bout of maximal sprint cycling; (3) a 40-min period of leg warming in a hot water bath at 42°C. Prior sprint exercise elevated blood [lactate] prior to the onset of heavy exercise (by ≅5.6 mM) with only a minor increase in muscle temperature (of ≅0.7°C). In contrast, prior warming had no effect on baseline blood lactate concentration, but elevated muscle temperature by ≅2.6°C. Both prior heavy exercise and prior sprint exercise significantly increased the absolute primary $\dot{V}O_2$ amplitude (by ≅230 ml·min^{-1} and 260 ml·min^{-1}, respectively) and reduced the amplitude of the $\dot{V}O_2$ slow component (by ≅280 ml·min^{-1} and 200 ml·min^{-1}, respectively) during heavy exercise, whereas prior warming had no significant effect on the $\dot{V}O_2$ response. We conclude that the $\dot{V}O_2$ response to heavy exercise can be markedly altered by both sustained heavy-intensity submaximal exercise and by short-duration sprint exercise that induces a residual acidosis. In contrast, passive warming elevated muscle temperature but had no effect on the $\dot{V}O_2$ response.

Keywords $\dot{V}O_2$ response · Prior exercise · $\dot{V}O_2$ slow component · Muscle temperature

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Introduction

It is well established that a prior bout of heavy exercise (above the lactate threshold, Th_{la}) affects the time course of the pulmonary oxygen uptake ($\dot{V}O_2$) response to heavy exercise (Bohnert et al. 1998; Gerbino et al. 1996; MacDonald et al. 1997). These studies demonstrated that the overall adaptation of $\dot{V}O_2$ was faster and the amplitude of the $\dot{V}O_2$ slow component was reduced during the second of two bouts of heavy exercise. In two recent reports (Burnley et al. 2000, 2001), we employed analytical procedures that characterised the three temporal phases of the $\dot{V}O_2$ response to heavy exercise (the initial "cardiodynamic" component, the subsequent primary component and the delayed slow component; Barstow et al. 1996). From these analyses, we established that prior heavy exercise did not speed the kinetics of the primary $\dot{V}O_2$ response (Burnley et al. 2000), but rather increased the amplitude of the primary response and decreased the amplitude of the slow component response (Burnley et al. 2001).

The mechanisms underlying the effect of prior heavy exercise remain to be established. However, prior moderate-intensity exercise has no effect on the $\dot{V}O_2$ response to subsequent heavy exercise (Burnley et al. 2000; Gerbino et al. 1996), even when the bout is extended so that the total work done is the same as that during a bout of heavy exercise (Burnley et al. 2001). This indicates that a metabolic acidosis is necessary for the $\dot{V}O_2$

response profile to be altered in the second exercise bout. Gerbino et al. (1996) proposed that the residual acidosis that is present following the first bout of heavy exercise might promote vasodilatation and muscle perfusion and therefore offset a deficiency in oxygen availability at the onset of the second bout of heavy exercise. In addition, elevated blood lactate concentration ([lactate]) per se could increase whole-body $\dot{V}O_2$ during exercise, by stimulating mitochondrial respiration (Stringer et al. 1994; Willis and Jackman 1994). However, empirical evidence for these potential effects on the $\dot{V}O_2$ response in exercising humans is limited. For example, it has been shown that infusions of adrenaline markedly elevate blood [lactate] without altering $\dot{V}O_2$ during heavy exercise (Gaesser et al. 1994).

In previous studies, the initial bout of heavy exercise has been identical to that of the second bout (generally 6 min at 50% of the difference between Th_{la} and peak $\dot{V}O_2$, $\dot{V}O_{2peak}$; Burnley et al. 2000; Gerbino et al. 1996; MacDonald et al. 1997; Scheuermann et al. 2001). Bohnert et al. (1998) showed that a bout of prior high-intensity arm crank exercise had qualitatively similar effects on the $\dot{V}O_2$ kinetics during subsequent heavy leg cycle exercise, although the magnitude of the effect was not as great. It is not known what effect the type of high-intensity exercise (e.g. sustained heavy exercise or short-duration sprint exercise) performed by the same muscle group (i.e. the legs) has on the $\dot{V}O_2$ response to subsequent exercise. For example, if acidosis is an important mediator of the effects observed, then prior sprint exercise, which should result in a higher residual blood [lactate] than prior heavy exercise, might amplify these effects.

Prior exercise will elevate muscle temperature and it has been suggested that this stimulates whole-body $\dot{V}O_2$ (Hagberg et al. 1978; Willis and Jackman 1994). However, relatively few studies have investigated the effect of muscle warming on the $\dot{V}O_2$ response during exercise. Koga et al. (1997) reported that increasing muscle temperature had no effect on the primary $\dot{V}O_2$ response, but that it led to a significant reduction in the $\dot{V}O_2$ slow component. In contrast, Ferguson et al. (1998) demonstrated that increasing muscle temperature led to greater $\dot{V}O_2$ during heavy cycle exercise at 60 rpm, although they did not partition the response into its constituent phases. Additional studies are necessary to clarify the role of elevated muscle temperature on the $\dot{V}O_2$ response to heavy exercise.

The purpose of this study was to determine whether prior short-duration sprint exercise could exert similar effects on the $\dot{V}O_2$ response to heavy exercise to that observed following an identical bout of heavy exercise. A secondary purpose of the present study was to re-examine the effect of elevated muscle temperature on the $\dot{V}O_2$ response to heavy exercise.

Methods

Subjects

Nine healthy males volunteered to participate in this study, which was approved by the Institutional Ethics Committee. The subjects were involved in recreational sports activities and their physical characteristics are presented in Table 1.

Experimental design

The subjects reported to the laboratory on seven occasions over a 2-week period. The first test was used to determine the Th_{la} and $\dot{V}O_{2peak}$ and to familiarise the subjects with the performance of isokinetic cycle sprinting. Subsequently, subjects returned to the laboratory for six separate visits in order to complete the experimental testing. The study was designed to examine the $\dot{V}O_2$ response to heavy exercise following each of three conditions: (1) a bout of heavy exercise as performed in previous studies (e.g. Burnley et al. 2000; Gerbino et al. 1996); (2) a bout of sprint exercise, resulting in an exercise-induced elevation in blood [lactate] with presumably only a minor increase in muscle temperature; (3) a period of passive warming of the lower limbs in a hot bath, resulting in increased muscle temperature without a residual increase in blood [lactate]. The subjects performed two repetitions of these tests in a random order. Each laboratory session was separated by at least 24 h, and subjects were instructed to arrive in a rested, well-hydrated state, having consumed no food or alcohol for at least 3 h prior to testing. Exercise testing was performed at approximately the same time of day for each subject.

Measurement of Th_{la} and $\dot{V}O_{2peak}$

All exercise testing was performed on an electrically braked cycle ergometer (Jaeger ER800, Germany). The saddle and handlebar position on the cycle ergometer were recorded on the first visit and replicated on subsequent exercise tests. Each subject self-selected a cadence of between 70 and 95 rpm and maintained this throughout

Table 1. Subjects' physical characteristics. (Th_{la} Lactate threshold, $\dot{V}O_{2peak}$ peak oxygen uptake)

Subject	Age (years)	Height (m)	Mass (kg)	Th_{la} ($l \cdot min^{-1}$)	$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)
1	22	1.82	66.9	3.10	4.38	65
2	31	1.75	73.2	2.91	3.94	54
3	34	1.76	88.1	2.31	4.50	51
4	22	1.80	71.1	2.46	4.03	57
5	22	1.81	76.1	1.93	3.92	52
6	22	1.81	76.4	2.51	3.45	45
7	25	1.84	69.4	1.93	3.36	48
8	27	1.76	75.7	2.19	3.30	44
9	37	1.92	94.0	2.28	4.08	43
Mean	27	1.81	76.8	2.40	3.88	51
SD	6	0.05	8.8	0.40	0.43	7

all subsequent tests on this ergometer. The Th_{la} and $\dot{V}O_{2peak}$ were determined from an incremental cycle protocol. The tests began at a power output of 50–100 W, and the power output was increased by 25 W every 4 min. At the end of each 4-min stage, a blood sample (≅25 μl) was collected from the fingertip into a capillary tube for immediate analysis of blood [lactate] using an automated lactate analyser (YSI Stat 2300, Yellow Springs, Ohio, USA). This analyser was calibrated hourly with a 5 mM lactate standard supplied by the manufacturer (YSI 2747). The subjects completed between six and nine 4-min stages and the test was terminated when blood [lactate] increased by 1 mM or more on two consecutive stages. When the 4-min stages were completed, the power output was increased incrementally by 25 W every minute until the subjects reached volitional exhaustion. Throughout the incremental test, pulmonary gas exchange was measured breath-by-breath, as described below. The "steady-state" $\dot{V}O_2$ for a given power output was taken as that measured over the last 30 s of each 4-min stage, while peak $\dot{V}O_2$ was determined as the highest value recorded in any 30-s period prior to the subject's volitional termination of the test. The Th_{la} was determined as the first sustained increase in blood [lactate] above resting levels from visual inspection of individual plots of blood [lactate] versus $\dot{V}O_2$ by two experienced, independent reviewers.

Experimental tests

Prior heavy exercise protocol

This protocol was the same as that used in previous studies (e.g. Burnley et al. 2000). Briefly, subjects performed two 6-min bouts of heavy exercise (at a power output half-way between Th_{la} and $\dot{V}O_{2peak}$; 50% Δ) on the electrically braked ergometer. The initial bout of heavy exercise was preceded by 3 min of pedalling at 20 W, and the two heavy exercise bouts were separated by 6 min of pedalling at 20 W. Throughout this test, pulmonary gas exchange was measured breath-by-breath, as described herein. Immediately before and after each heavy exercise bout, a fingertip blood sample was taken for the determination of capillary whole-blood [lactate].

Prior sprint exercise protocol

For this protocol, a 30-s period of all-out sprint exercise preceded the heavy exercise bout. The ergometer, a composite of a conventional bicycle frame and a Monark ergometer, was bolted firmly to the superstructure of a tooth-driven high-speed treadmill (Woodway ELG2, Cardiokinetics, Salford, UK). The power output applied to the cranks of the ergometer was measured using a commercially available instrumented crank system (SRM Powercrank, Julich, Germany).

Subjects began by mounting the isokinetic ergometer without warming up, with the saddle height adjusted to match that of the electrically braked cycle ergometer. Once this was completed, subjects were instructed to assume the "ready" position (with the starting leg in a position such that the crank arm of the pedal was level with the down tube of the ergometer). The treadmill belt speed was increased to 17.1 $km \cdot h^{-1}$, a speed that would elicit a maximum cadence of 120 rpm, and subjects were instructed to signal their readiness to sprint. When this was received, subjects sprinted all-out for 30 s following a verbal 3-s countdown. The only feedback given to the subjects was the verbal call of time elapsed every 5 s. On the call of 30 s, subjects were instructed to stop sprinting.

Subjects were allowed to spin the legs for a maximum of 30 s following the sprint; most chose to simply dismount the ergometer at the end of the test. A stop-clock was started at the conclusion of the sprint to time the 6-min recovery period. Subjects were transferred to the electrically braked ergometer and fitted with the head gear, mouthpiece and nose clip of the respiratory apparatus for the measurement of pulmonary gas exchange. After 3 min of recovery, subjects were instructed to start pedalling at their preferred cadence, and a 3-min period of baseline pedalling began (at 20 W). At this point, data acquisition by the mass spectrometer and turbine volume transducer also began. Heavy exercise commenced immediately after this baseline period, effected by a square-wave increase in power output to 50% Δ. This was maintained for 6 min, and was followed by 6 min of pedalling at 20 W. Pulmonary gas exchange was measured throughout these heavy exercise and recovery bouts, and fingertip blood samples for determination of blood [lactate] were also taken immediately before and after heavy exercise.

Prior warming protocol

In this protocol, the 6-min bout of heavy exercise was preceded by a 40-min period of passive lower-limb warming in a bath containing water at 42°C. This warming procedure has been shown to increase muscle temperature by ≅3°C (Rademaker 1997). The hot water bath was situated in a room adjacent to the laboratory containing the electrically braked cycle ergometer and mass spectrometer. Subjects were prepared for the tank by removing all clothing except a pair of shorts or swimming trunks. Each subject retired to insert a rectal probe (Kendall, Ireland) 10 cm beyond the anal sphincter. One subject did not consent to this procedure. Prior to immersion, the level of the tank water was set 2 cm below the level of the gluteal fold in order to accommodate lower limb volume. Once the water had reached 42°C, subjects slowly entered the water and stood upright, usually resting the arms on the side of the tank. Both rectal and tank temperatures were monitored throughout the 40-min immersion (rectal temperature, Libra Medical, Berkshire, UK; tank temperature, 1000 Series Squirrel meter, Grant, Cambridge, UK). The probe measuring tank temperature was placed 30 cm below the waterline. Tank and rectal temperatures were recorded every 5 min and the tank was regularly stirred to prevent thermal stratification. The water temperature was adjusted to ensure that it did not drop below 41°C in any trial. Drinking water was provided and subjects were allowed to consume it ad libitum.

At the end of the 40-min period of immersion, subjects left the tank, towelled down and changed into cycling attire. Within 3 min, subjects were escorted into the adjacent laboratory and mounted the electrically braked ergometer. Following the attachment of the subject to the respiratory mouthpiece, subjects again performed the 3 min of 20-W pedalling, 6 min of heavy exercise and 6 min of recovery in the same fashion as during the prior sprint protocol. Again, pulmonary gas exchange was measured breath-by-breath throughout the cycling period and fingertip blood samples were taken immediately before and after heavy exercise.

Measurement of muscle temperature (T_m)

On a separate occasion, five of the subjects gave their written informed consent to the measurement of T_m before and after the prior sprinting and prior warming trials. Each trial began with the subjects sitting on a laboratory bench in shorts to allow the measurement of T_m using a needle thermocouple (Ellab A/S, type A-K8, Copenhagen, Denmark), which was inserted into the vastus lateralis at mid-thigh slightly lateral to the femur (Rademaker 1997). The site of insertion was thoroughly cleaned with an alcohol swab prior to the insertion of the needle, wherein temperature was measured within 15 s of insertion at depths of approximately 3 and 2 cm. In both trials, T_m measurements were again made 6 min after the completion of the sprinting or warming. These measurements would therefore represent the muscle temperature at the onset of heavy exercise following these treatments. Mean T_m was recorded as the average of the 2- and 3-cm readings in each insertion. The individual thermocouples were calibrated by submersion in water at three known temperatures ranging from 20°C to 50°C.

Measurement of pulmonary gas exchange

Pulmonary gas exchange was measured breath-by-breath throughout all tests. Subjects wore a nose clip and breathed

through a mouthpiece connected to a low-resistance (0.65 $cmH_2O \cdot l^{-1} \cdot s^{-1}$, where 1 $mmH_2O = 9.8\ N \cdot m^{-2}$, at 8.5 $l \cdot s^{-1}$) turbine volume transducer for the measurement of inspiratory and expiratory volumes (Interface Associates, Calif., USA). The turbine was calibrated using a 3-l calibration syringe (Hans Rudolph, Kansas, USA). The dead space volume of the mouthpiece was 90 ml. A 2-m-long capillary tube was used to continuously draw gas from the mouthpiece into a mass spectrometer (CaSE QP9000, Morgan Medical, Kent, UK) at a rate of 60 $ml \cdot min^{-1}$. The mass spectrometer was tuned to measure oxygen, carbon dioxide and nitrogen concentrations at a rate of 50 Hz, and was calibrated before each test using gases of known concentration (British Oxygen Company, London, UK). Volume and concentration signals underwent time alignment and analog-to-digital conversion, and breath-by-breath values for $\dot{V}O_2$, carbon dioxide output and expired ventilation were calculated and displayed on-line. Heart rate was monitored continuously using short-range telemetry (Polar Sports Tester, Kempele, Finland).

Data analysis

The breath-by-breath data were linearly interpolated to provided second-by-second values. For each subject, the two performances of each protocol were time aligned and averaged to provide one set of second-by-second data for each variation of the protocol. The time course of the $\dot{V}O_2$ response after the onset of exercise was described in terms of a three-component exponential function, using iterative non-linear regression techniques in which minimising the sum of the squared error was the criterion for convergence, using purpose-built fitting software. Each exponential curve was used to describe one phase of the response. The first phase began at the onset of exercise, whereas the other terms began after independent time delays (Barstow et al. 1996):

$$\dot{V}O_2(t) = \dot{V}O_2(b) + A_c * \left(1 - e^{-(t/\tau c)}\right) \quad \text{Phase I (cardiodynamic component)}$$
$$+ A_p * \left(1 - e^{-(t/TD1)/\tau p}\right) \text{Phase II (primary component)}$$
$$+ A_s * \left(1 - e^{-(t/TD2)/\tau s}\right) \text{Phase III (slow component)} \qquad (1)$$

where $\dot{V}O_2(b)$ is the baseline $\dot{V}O_2$ measured in the 3 min preceding the onset of exercise; A_p and A_s are the amplitudes of the exponential curves fitting the primary and slow components respectively, τ_p and τ_s are the time constants and TD_1 and TD_2 are the time delays. The cardiodynamic component was terminated at TD_1, and given the value for that time (i.e. A'_c, where $A'_c = A_c\left(1 - e^{-(-TD1/\tau c)}\right)$). The amplitude of the primary response (A'_p) was defined as the increase in $\dot{V}O_2$ from baseline to the asymptote of the primary component (i.e. $A'_c + A_p$). The absolute amplitude of the primary $\dot{V}O_2$ response was calculated as the sum of baseline $\dot{V}O_2$ and A'_p. The amplitude of the $\dot{V}O_2$ slow component was determined as the increase in $\dot{V}O_2$ from TD_2 to the end of exercise (defined A'_s), rather than from the asymptotic value (A_s), which may project beyond the value at 6 min (end exercise).

Statistical analysis

The responses to the square-wave bouts of heavy exercise were compared using a one-way repeated measures analysis of variance with post hoc Bonferroni-adjusted paired-samples confidence intervals. The relevant responses compared were the responses to initial heavy exercise, heavy exercise after prior heavy exercise, heavy exercise after prior sprinting, and heavy exercise after prior warming. The effect of the prior conditions on muscle and rectal temperatures were analysed using Student's paired samples *t*-tests. The *F*-ratios and *t*-values were considered statistically significant when $P < 0.05$. Values are presented as mean (SD) unless stated otherwise.

Results

The constant-intensity heavy exercise bouts were performed at a power output of 255 (26) W, requiring a total work output over 6 min of 91.8 (9.4) kJ. During the sprinting trials, subjects produced a peak power output of 987 (74) W and a mean power output of 655 (60) W, with a corresponding work output over the 30 s of 19.8 (1.8) kJ.

Passive warming of the lower legs in the hot water bath resulted in a significant increase in both T_m ($n = 5$) and rectal temperature [$n = 8$; resting, 37.3 (0.2)°C; exit of bath 37.9 (0.3)°C, $t_7 = 4.15$; $P = 0.004$]. Mean T_m (the average of the 2- and 3-cm measurements) was increased by 2.6°C after the prior warming ($t_4 = 9.93$; $P = 0.001$) and by 0.7°C after prior sprinting ($t_4 = 2.45$ $P = 0.07$). As shown in Table 2, the mean T_m measured after prior warming was 1.6°C higher than after prior sprinting.

Effects of prior heavy exercise

The initial bout of heavy exercise in this protocol elevated both baseline $\dot{V}O_2$ ($F_{3,8} = 34.55$; $P < 0.001$) and baseline blood [lactate] prior to the second heavy exercise bout ($F_{3,8} = 108.57$; $P < 0.001$; Table 2). Prior heavy exercise did not alter either τ_p ($F_{3,8} = 1.16$; $P = 0.35$) or A'_p [1.95 (0.11) vs 2.07 (0.11) $l \cdot min^{-1}$; $F_{3,8} = 0.41$; $P = 0.75$]. However, the absolute amplitude of the primary $\dot{V}O_2$ response ($\dot{V}O_2(b) + A'_p$) was significantly increased by prior heavy exercise [2.85 (0.09) vs 3.08 (0.09) $l \cdot min^{-1}$; $F_{3,8} = 21.00$; $P < 0.001$], whilst the amplitude of the $\dot{V}O_2$ slow component (A'_s) was subsequently reduced ($F_{3,8} = 13.74$; $P < 0.001$). In addition to the reduction in the $\dot{V}O_2$ slow component, Δ blood [lactate] was reduced following prior heavy exercise ($F_{3,8} = 105.67$; $P < 0.001$), although neither the end-exercise blood [lactate], nor the end-exercise $\dot{V}O_2$ responses differed from the initial bout of heavy exercise (Table 2).

Effects of prior sprint exercise

The responses to heavy exercise following the sprint were qualitatively similar to those following prior heavy exercise. However, after the sprint bout, heavy exercise commenced with a significantly higher baseline blood [lactate], and a slightly higher baseline $\dot{V}O_2$ than after prior heavy exercise (Table 2). Prior sprint exercise did not alter τ_p or A'_p. However, the absolute amplitude of the primary $\dot{V}O_2$ response was increased by $\cong$260 $ml \cdot min^{-1}$ and the $\dot{V}O_2$ slow component was reduced by $\cong$200 $ml \cdot min^{-1}$ after sprint exercise, these values being similar to the effects of prior heavy exercise on the $\dot{V}O_2$ response. The relatively high baseline blood [lactate] observed following sprint exercise was associated with a very small Δ blood [lactate] response to heavy exercise, this being considerably smaller than for the other

Table 2. Parameters of the oxygen uptake ($\dot{V}O_2$) and blood lactate responses to heavy exercise. Data are presented as the mean (SEM). ($\dot{V}O_2(b)$ Baseline $\dot{V}O_2$, T_m muscle temperature, *EE* end exercise, *TD* time delay, τ_p time constant of the $\dot{V}O_2$ primary response, τ_s time constant of the $\dot{V}O_2$ slow component, A'_p amplitude of the $\dot{V}O_2$ primary response, A'_s amplitude of the $\dot{V}O_2$ slow component, [lactate] lactate concentration)

	Initial heavy exercise	After heavy	After sprint	After warming
$\dot{V}O_2$(b)	0.90 (0.03)	1.01 (0.05)*·***	1.14 (0.04)*·**	0.90 (0.04)**·***
Baseline [lactate] (mM)	0.8 (0.1)	3.4 (0.3)*·***	6.4 (0.4)*·**	0.7 (0.1)**·***
Baseline T_m (°C)			37.0 (0.4)	38.6 (0.3)***
Primary phase				
TD_1 (s)	21.0 (1.0)	17.5 (1.0)	14.8 (0.7)*	18.8 (1.3)
τ_p (s)	23.1 (1.6)	26.9 (2.5)	24.6 (1.6)	26.8 (2.3)
A'_p (l·min^{-1})	1.95 (0.11)	2.07 (0.11)	1.98 (0.09)	2.00 (0.12)
$\dot{V}O_2(b) + A'_p$ (l·min^{-1})	2.85 (0.09)	3.08 (0.09)*	3.11 (0.09)*	2.90 (0.11)**·***
Slow component				
TD_2 (s)	89.2 (5.9)	103.8 (7.6)	83.7 (5.0)	95.9 (8.2)
τ_s (s)	216.6 (12.6)	234.2 (12.8)	277.3 (16.8)*	219.4 (22.2)
A'_s (l·min^{-1})	0.47 (0.06)	0.19 (0.05)*	0.27 (0.06)*	0.38 (0.08)**
Overall response				
Absolute EE $\dot{V}O_2$ (l·min^{-1})	3.33 (0.11)	3.27 (0.11)	3.38 (0.12)**	3.28 (0.14)
EE [lactate] (mM)	4.8 (0.3)	5.1 (0.4)	6.8 (0.3)*·**	4.5 (0.3)***
Δ [lactate] (mM)	3.9 (0.3)	1.7 (0.2)*·***	0.3 (0.3)*·**	3.8 (0.3)**·***
Δ T_m (°C)			0.7 (0.3)	2.6 (0.3)***

*Significantly different from Initial heavy exercise ($P < 0.05$)
**Significantly different from after heavy ($P < 0.05$)
***Significantly different from after sprint ($P < 0.05$)

conditions (Table 2). However, the end-exercise blood [lactate] after sprint exercise was 1.7 mM higher, on average, than for any of the other conditions ($F_{3,8} = 17.36$; $P < 0.001$). Furthermore, the end-exercise $\dot{V}O_2$ response to heavy exercise was slightly but significantly higher following sprint exercise than following prior heavy exercise (Table 2).

Effects of prior warming

Elevating leg muscle temperature by, on average, 2.6°C by 40 min of prior warming in a water bath at 42°C had no effect on the $\dot{V}O_2$ or blood [lactate] responses to heavy exercise. As shown in Table 2, the values for the $\dot{V}O_2$ and blood [lactate] response both under baseline conditions, and in response to heavy exercise, are similar to the initial bout of heavy exercise in the prior heavy protocol. In contrast to both prior heavy exercise and prior sprint exercise, prior warming did not increase the absolute primary $\dot{V}O_2$ amplitude, or reduce the amplitude of the $\dot{V}O_2$ slow component. The blood [lactate] responses to heavy exercise following prior warming were strikingly similar to those of the initial bout of heavy exercise.

Comparison of the three experimental conditions

The effects of the three treatment conditions (prior heavy exercise, prior sprint exercise and prior warming) are shown graphically in Fig. 1. Fig. 1A–C represent the $\dot{V}O_2$ responses to heavy exercise in the three respective conditions superimposed on the $\dot{V}O_2$ response to the initial bout of heavy exercise. What is evident from this comparison is the increase in primary $\dot{V}O_2$ amplitude following heavy exercise (A) and sprint exercise (B). Further, the reduced amplitude of the $\dot{V}O_2$ slow component after both heavy exercise and sprint exercise leads to a convergence of the $\dot{V}O_2$ responses at 6 min. In contrast, Fig. 1C (prior warming superimposed on initial heavy exercise) shows none of these differences, the $\dot{V}O_2$ response after prior warming being similar to the initial bout of heavy exercise.

Discussion

The present investigation has demonstrated that prior sprint exercise, which induced a residual lactic acidosis, influenced the $\dot{V}O_2$ response to subsequent heavy exercise in a manner similar to that of a prior bout of heavy exercise. Both of these prior conditions resulted in an increase in the absolute amplitude of the primary $\dot{V}O_2$ response and reduced the amplitude of the $\dot{V}O_2$ slow component. In contrast, prior warming of the lower limbs in a hot bath did not alter the $\dot{V}O_2$ response to subsequent heavy exercise. The characteristic effects of prior exercise on the $\dot{V}O_2$ response, therefore, appear to be related to the performance of heavy exercise under conditions of a residual blood lactic acidosis, although the effect was no greater when baseline blood [lactate] was increased from ≅3.4 mM (heavy exercise) to ≅6.4 mM (sprint exercise).

Effects of prior heavy exercise and sprint exercise on heavy exercise $\dot{V}O_2$

Gerbino et al. (1996) were the first to demonstrate that a prior bout of high-intensity exercise can markedly alter the kinetics of $\dot{V}O_2$ during high-intensity exercise. The "effective time constant", calculated from ≅20 s to the end of exercise, indicated a speeding of the overall $\dot{V}O_2$ response, which the authors suggested might be related to increased O_2 delivery consequent to vasodilatation

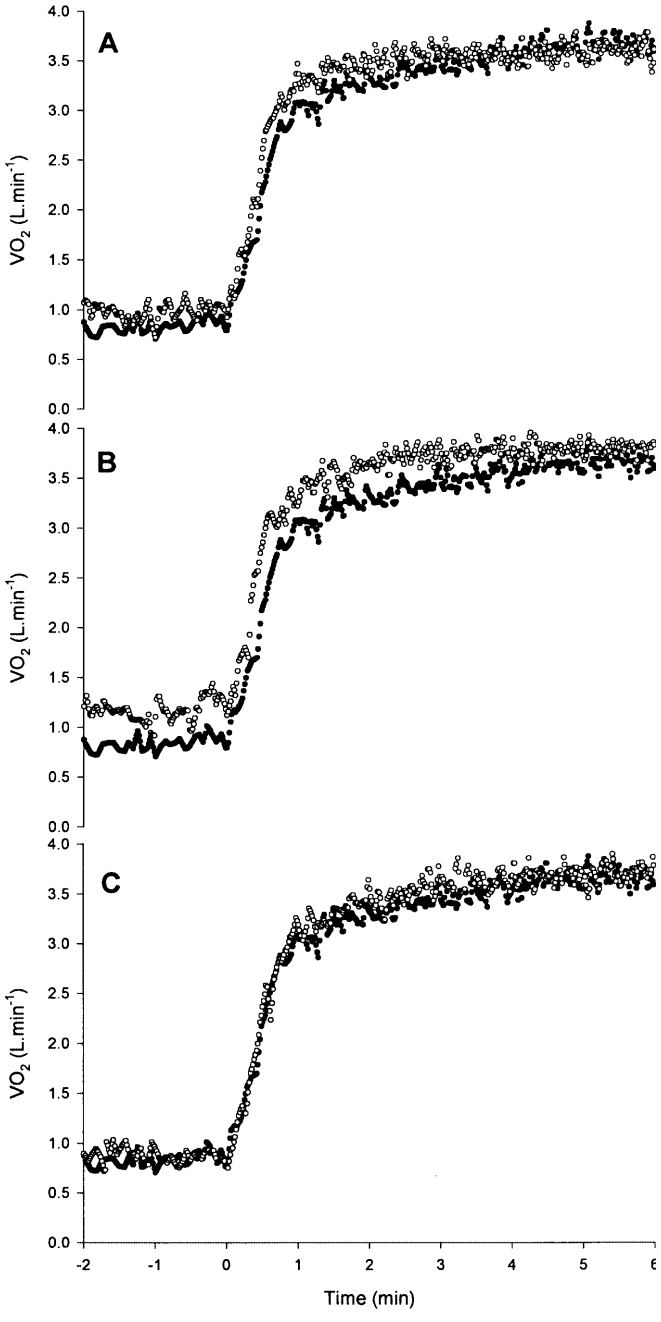

Fig. 1. Oxygen uptake responses to heavy exercise in a representative subject. Notice that prior heavy exercise (**A**) and prior sprint exercise (**B**) elicit similar oxygen uptake ($\dot{V}O_2$) responses to heavy exercise, whereas prior warming (**C**) appears to have no discernible effect on these responses. *Closed symbols* represent the first exercise bout and *open symbols* represent the bout performed following the treatment (prior heavy exercise, prior sprint exercise, or passive warming)

resulting from the residual acidosis. In the same study, Gerbino et al. (1996) demonstrated that neither prior moderate nor prior heavy exercise appreciably affected the $\dot{V}O_2$ response to moderate exercise. MacDonald et al. (1997) also reported faster overall $\dot{V}O_2$ kinetics, as reflected by the "mean response time", when heavy exercise was preceded by a priming bout of heavy exercise. Collectively, the results of Gerbino et al. (1996) and MacDonald et al. (1997) were interpreted to suggest that $\dot{V}O_2$ kinetics during heavy, but not moderate, exercise may be limited by O_2 delivery. Burnley et al. (2000) repeated the experiment and substantially confirmed the results of Gerbino et al. (1996). However, there was one important difference: when the data were modelled using separate exponential terms for the primary and slow components, the time constant of the primary response during heavy exercise was not changed by prior heavy exercise; rather, the absolute $\dot{V}O_2$ amplitude at the end of the primary phase was elevated and the amplitude of the $\dot{V}O_2$ slow component was correspondingly reduced. The present study provides further evidence that prior heavy exercise increases the absolute amplitude of the primary $\dot{V}O_2$ response, without changing the value of the primary $\dot{V}O_2$ time constant, and that it reduces the amplitude of the $\dot{V}O_2$ slow component during heavy exercise. These findings are consistent with our previous work (Burnley et al. 2000, 2001) and those of other laboratories (Koppo and Bouckaert 2001; Scheuermann et al. 2001). As considered previously (Burnley et al. 2000; Koppo and Bouckaert 2001; Scheuermann et al. 2001), these response profiles appear to be incompatible with the notion that O_2 delivery limits the rate of increase in $\dot{V}O_2$ during the primary component. The "speeding" of the mean response time or effective time constant for the overall $\dot{V}O_2$ response noted in these previous studies can result simply from an attenuation of the amplitude of the slow component, often with a corresponding increase in the amplitude of the primary component, but with no reduction in the time constant for the primary response (Burnley et al. 2000; Koppo and Bouckaert 2001; Scheuermann et al. 2001).

The elevated absolute primary $\dot{V}O_2$ amplitude and reduced $\dot{V}O_2$ slow component observed following prior heavy exercise was also a characteristic feature of the response following sprint exercise. A common feature of these conditions was the elevated baseline blood [lactate] at the onset of subsequent heavy exercise. However, the degree of elevation in baseline blood [lactate] was significantly greater following sprint exercise (≅6.4 mM) than following heavy exercise (≅3.4 mM), yet the effects on the $\dot{V}O_2$ response were similar. If lactate accumulation played a direct role in the treatment effect, then it should also have been possible to distinguish between the $\dot{V}O_2$ response in these conditions.

The accumulation of lactate and the pronounced fall in muscle pH that occurs during high-intensity exercise have long been associated with muscle fatigue (e.g. Hogan et al. 1995; Sahlin et al. 1998). A possible interpretation of the increase in the amplitude of the primary $\dot{V}O_2$ response and the subsequent reduction of the $\dot{V}O_2$ slow component could be that this reflects the recruitment of different or additional motor units at exercise onset due to an acidosis-mediated fatigue within previously recruited muscle fibres. However, perhaps the most compelling argument against fatigue mediating the

effects observed is that the key features of the response profile are the same when the duration of recovery is extended (Burnley et al. 2001; Patel et al. 2001). The increase in the amplitude of the primary $\dot{V}O_2$ response and the reduction in the amplitude of the $\dot{V}O_2$ slow component observed after 6 min of recovery from the initial exercise condition is still evident at least 12–15 min after the performance of heavy exercise (Burnley et al. 2001; Patel et al. 2001). The rapid restoration of maximal muscle power output after prior heavy exercise (Sargeant and Dolan 1987) and prior sprint exercise (Robach et al. 1997) suggests that fatigue-related phenomena cannot account for the response profiles illustrated in Fig. 1.

Baseline $\dot{V}O_2$ was elevated above pre-exercise levels after both prior heavy and prior sprint exercise. Our previous experiments using 12-min recovery periods (Burnley et al. 2001) showed that the increase in the absolute amplitude of the primary $\dot{V}O_2$ response consistently observed reflects a true increase in the net primary amplitude (A'_p), which is not identified with only 6-min recovery because baseline $\dot{V}O_2$ is elevated at the onset of exercise. To the extent that A'_p is thought to reflect the target O_2 demand at the onset of exercise, the present results suggest that both prior heavy exercise and prior sprint exercise increased this target O_2 demand. We have only been able to demonstrate this effect under conditions of an exercise-induced elevation in baseline blood [lactate] (Burnley et al. 2000, 2001). The recovery of other putative metabolic mediators, such as adrenaline, noradrenaline and K^+ following exercise may be too rapid to account for the effects observed (Bohnert et al. 1998). Timmons et al. (1998) reported that prior activation of the pyruvate dehydrogenase complex (PDC) by infusion of dichloroacetate led to a reduction in muscle lactate accumulation during heavy cycle exercise by increasing acetyl group availability to the mitochondria. The PDC is also activated by an increase of intra-mitochondrial [Ca^{2+}] at the onset of exercise (cf. Tschakovsky and Hughson 1999). The rate of post-exercise recovery of [Ca^{2+}] in the subcellular compartments is not known, but even small residual increases may be sufficient to stimulate an increase in mitochondrial respiration. However, increased activation of intra-mitochondrial enzymes through increased [Ca^{2+}] or acetyl group availability might be expected to speed the $\dot{V}O_2$ kinetics in the primary phase (Grassi et al. 1998; Tschakovsky and Hughson 1999), an effect that we did not observe. Rather, the elevated blood [lactate] observed at the onset of exercise, or an associated variable that may include an elevated muscle [lactate] and/or a reduced muscle pH (Allsop et al. 1991), appears to effect a physiological response that ultimately manifests itself as an increase in the primary $\dot{V}O_2$ response amplitude.

Recent studies in human muscle fibres demonstrated that severe acidosis caused by exhaustive high-intensity exercise increased the sensitivity of mitochondrial respiration to ADP (Tonkonogi et al. 1999), whereas exhaustive low-intensity exercise that did not cause a lactic acidosis, had no such effect (Tonkonogi et al. 1998). Futile proton pumping due to an increased leakage of protons across the inner mitochondrial membrane in state 4 of respiration will increase $\dot{V}O_2$ and may lower the P:O ratio (Tonkonogi and Sahlin 1999). On the other hand, in vivo studies using ^{31}P-nuclear magnetic resonance spectroscopy demonstrate a reduction in maximum $\dot{V}O_2$ during acidosis (Harkema and Meyer 1997), while in vitro studies demonstrate either a reduction (Mitchelson and Hird 1973) or an unchanged (Suleymanlar et al. 1992) maximal rate of mitochondrial respiration when pH is reduced to ≅6.4. Muscle heat production (Krustrup et al. 2001) and ATP turnover (Bangsbo et al. 2001) are apparently unchanged in the second of two bouts of high-intensity knee-extension exercise, indicating that any effect of reduced muscle pH on mechanical efficiency is small. In addition, Krustrup et al. (2001) argued that their measurement of an increased muscle O_2 extraction in the second of two high-intensity exercise bouts persisted for longer than any differences in muscle pH. On this evidence, it would appear that a reduction in muscle pH cannot be responsible for the increase in the primary $\dot{V}O_2$ response observed in the second exercise bout.

The amplitude of the $\dot{V}O_2$ primary component is linearly related to work rate such that the "gain" of the primary $\dot{V}O_2$ response is similar during moderate and heavy cycle exercise (≅10 $ml \cdot min^{-1} \cdot W^{-1}$ in normal subjects; Barstow and Molé 1991; Paterson and Whipp 1991). This has led to the suggestion that the amplitude of the primary $\dot{V}O_2$ component represents the expected $\dot{V}O_2$ requirement during heavy exercise, and that this requirement is modified with time following the emergence of the $\dot{V}O_2$ slow component after ≅90–150 s of exercise (Barstow and Molé 1991; Paterson and Whipp 1991). In the present study, the increase in the amplitude of the $\dot{V}O_2$ primary response towards the actual (as reflected by the end-exercise value), rather than the initially anticipated, $\dot{V}O_2$ requirement in the second bout of heavy exercise was of great interest. Differences in motor unit recruitment in the second compared to the first bout of heavy exercise may provide a feasible mechanism for the effect on the $\dot{V}O_2$ responses. Approximately 86% of the $\dot{V}O_2$ slow component arises from within the exercising limbs (Poole et al. 1991), and subjects with a higher proportion of type II fibres in the vastus lateralis demonstrated a greater slow component during heavy exercise (Barstow et al. 1996). Increased motor unit recruitment for the same external power output would seem to represent a favourable adaptation from the standpoint of sustaining heavy exercise, since the tension each recruited fibre needs to generate, and thus the metabolic disturbance imposed on each fibre, would be reduced. It seems reasonable to suggest, therefore, that the effects of prior heavy exercise (reduced $\dot{V}O_2$ slow component and reduced Δblood [lactate]) may result from the increase in the primary $\dot{V}O_2$ amplitude consequent to additional motor unit recruitment and the

smaller resulting metabolic disturbance at the individual fibre level. An increase in muscle activity during the second of two bouts of heavy exercise has been identified in two preliminary reports (Bearden and Moffatt 2000; Burnley et al. 2002). The mediator(s) of any increase in motor unit recruitment remains unclear. The presence of a lactic acidosis appears to be important, although its effect may not be related to its association with fatigue (see above).

Effect of elevated muscle temperature on heavy exercise $\dot{V}O_2$

Relatively few previous studies have investigated the effect of muscle temperature on $\dot{V}O_2$ kinetics during heavy exercise. In the present study, prior warming of the lower limbs had no effect on either the $\dot{V}O_2$ primary or slow component responses to heavy exercise. Koga et al. (1997) reported that prior muscle warming did not affect the primary $\dot{V}O_2$ response to heavy exercise, but that it significantly reduced the amplitude of the $\dot{V}O_2$ slow component during heavy exercise. Our results concur with those of Ingjer and Stromme (1979), who showed that passive warming (subjects immersed to the neck) had no effect on the $\dot{V}O_2$ or blood lactate responses to constant-intensity treadmill running at 100% maximum $\dot{V}O_2$, despite muscle temperature being elevated by ≅2.4°C at the onset of exercise. The fact that neither the $\dot{V}O_2$ nor the blood [lactate] response to heavy exercise was affected by prior muscle warming indicates that this procedure did not markedly influence the activity of the key hormones affecting metabolism.

It has been suggested that increases in T_m influence the $\dot{V}O_2$ response to heavy exercise via a Q_{10} effect on mitochondrial respiration (Hagberg et al. 1978) or proton back-leak through the inner mitochondrial membrane (Willis and Jackman 1994). However, oxidative phosphorylation in skeletal muscle is largely under feedback control, either through changes in phosphocreatine concentration or the phosphorylation potential ([ATP]/[ADP]+[Pi]), as a consequence of step changes in myosin ATPase activity (cf. Tschakovsky and Hughson 1999). This process is unlikely to be greatly affected by temperature changes in the physiological range (from ≅35°C to ≅40°C). This assertion is supported by the observation that mitochondrial function and physical performance only appear to be compromised at intramuscular temperatures exceeding 40°C (Febbraio 2000). Increased exercising T_m does not, therefore, appear to contribute to the characteristic effects of prior heavy exercise on the $\dot{V}O_2$ response to heavy exercise.

In conclusion, the present study has shown that 6 min of prior heavy exercise and 30 s of prior sprint exercise, both of which induced a residual lactic acidosis prior to the onset of heavy exercise, increased the amplitude of the primary $\dot{V}O_2$ response and reduced the amplitude of the $\dot{V}O_2$ slow component. However, the magnitude of the effect on the $\dot{V}O_2$ responses was similar despite blood [lactate] being significantly higher following the sprint exercise bout. This study has also confirmed that the effect of prior heavy exercise on the $\dot{V}O_2$ responses to heavy exercise is not related to elevated intra-muscular temperature. The physiological mechanism(s) mediating the effect of prior high-intensity exercise on the $\dot{V}O_2$ response to subsequent heavy exercise remain to be established.

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