Effect of prior exercise on pulmonary O$_2$ uptake and estimated muscle capillary blood flow kinetics during moderate-intensity field running in men

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Buchheit M, Laursen PB, Ahmaidi S. Effect of prior exercise on pulmonary O$_2$ uptake and estimated muscle capillary blood flow kinetics during moderate-intensity field running in men. J Appl Physiol 107: 460–470, 2009. First published June 4, 2009; doi:10.1152/japplphysiol.91625.2008.—The effect of prior exercise on pulmonary O$_2$ uptake (V$_{O_2,p}$) and estimated muscle capillary blood flow (Q$_{m}$) kinetics during moderate-intensity field-based running was examined in 14 young adult men, presenting with either moderately fast (16 s < V$_{O_2,p}$ < 30 s; MFK) or very fast V$_{O_2,p}$ kinetics (τV$_{O_2,p}$ < 16 s; VFK) (i.e., primary time constant, τV$_{O_2,p}$). On four occasions, participants completed a square-wave protocol involving two bouts of running at 90–95% of estimated lactate threshold (Mod1 and Mod2), separated by 2 min of repeated supramaximal sprinting. V$_{O_2,p}$ was measured breath by breath, heart rate (HR) beat to beat, and vastus lateralis oxygenation (deoxy-hemoglobin/myoglobin concentration (deoxy-[Hb+Mb])) using near-infrared spectroscopy. Mean response time of Q$_{m}$ (Q$_{m}$ MRT) was estimated by rearranging the Fick equation, using V$_{O_2,p}$ and deoxy-[Hb+Mb] as proxies of muscle O$_2$ uptake (V$_{O_2}$) and arteriovenous difference, respectively. HR, blood lactate concentration, total hemoglobin, and Q$_{m}$ were elevated before Mod2 compared with Mod1 (all P < 0.05). τV$_{O_2,p}$ was shorter in VFK compared with MFK during Mod1 (13.1 ± 1.8 vs. 21.0 ± 2.5 s, P < 0.01), but not in Mod2 (12.9 ± 1.5 vs. 13.7 ± 3.8 s, P = 1.0). Q$_{m}$ MRT was shorter in VFK compared with MFK in Mod1 (8.8 ± 1.9 vs. 17.0 ± 3.4 s, P < 0.01), but not in Mod2 (10.1 ± 1.8 vs. 10.5 ± 3.5 s, P = 1.0). During Mod2, HR kinetics were slowed, whereas mean deoxy-[Hb+Mb] response time was unchanged. The difference in τV$_{O_2,p}$ between Mod1 and Mod2 was related to Q$_{m}$ MRT measured at Mod1 (r = 0.71, P < 0.01). Present results suggest that local O$_2$ delivery (i.e., Q$_{m}$) may be a factor contributing to the V$_{O_2,p}$ kinetic during the onset of moderate-intensity, field-based running exercise, at least in subjects exhibiting moderately fast V$_{O_2,p}$ kinetics.

oxgen uptake dynamics; near-infrared spectroscopy; muscle deoxygenation; repeated sprint exercise; warm-up

COMMENCEMENT OF EXERCISE INSTIGATES an increase in O$_2$ delivery to working muscles to support the required increase in muscle oxygen uptake (V$_{O_2}$; V$_{O_2,m}$). However, the kinetics supporting the V$_{O_2,m}$ at exercise onset, now shown convincingly to be inferred from the pulmonary V$_{O_2,p}$ (27, 37), are still debated (40). Resolution of our knowledge surrounding whether V$_{O_2,m}$ is limited by adequate delivery of O$_2$ and/or other substrates required for mitochondrial oxidative phosphorylation (i.e., metabolic inertia) is essential for understanding metabolic control in health, the mechanics of impaired (slowed) V$_{O_2,m}$ kinetics found in patient populations (25, 26), and, eventually, for the design of appropriate exercise training interventions (3).

The current viewpoint surrounding the O$_2$ delivery/metabolic inertia debate is that it is a false dichotomy; that is, there may be a “tipping point” in the relationship between the speed of the V$_{O_2,p}$ kinetics [expressed using the time constant (τ) of the primary component (i.e., phase II) of V$_{O_2,p}$ (τV$_{O_2,p}$)] and muscle O$_2$ delivery (40). As highlighted by Poole et al. (40), the kinetics to the left of this tipping point (i.e., short τV$_{O_2,p}$) appear to be more essentially O$_2$-delivery dependent, whereas the right side is more likely determined by the availability of other substrates limiting O$_2$ utilization. It is, however, worth noting that the tipping point is more of a terminological concept than a real physiological variable or a parameter that we can currently measure. Mechanistic exploration into the basis of V$_{O_2,p}$ kinetics have used “priming” exercises in the past (e.g., Refs. 7, 10, 11, 19, 24, 28, 29). Compared with exercise transition without warm-up, V$_{O_2,p}$ kinetics upon initiation of heavy exercise subsequent to intense exercise appear consistently accelerated (the “overall” V$_{O_2,p}$ kinetics being significantly faster, due predominantly to a marked reduction in the amplitude of the so-called V$_{O_2,p}$ “slow component”). Mechanisms put forward to explain this phenomenon hint at enhanced muscle O$_2$ supply and delivery [i.e., increased cardiac output, muscle blood flow (Q$_{m}$) and total hemoglobin (tHb), or blood acidosis enhancing O$_2$ dissociation from Hb], and/or partial relief of muscle oxidative metabolic inertia [i.e., faster enzyme activation and improved substrate provision, illustrated by a shorter time delay (TD) before near-infrared spectroscopy (NIRS) muscle deoxygenation; deoxy-Hb/myoglobin concentration (deoxy-[Hb+Mb])], and/or alterations in motor unit recruitment profiles (for review, see Ref. 12).

Studies examining the effect of prior heavy exercise on V$_{O_2,p}$ adaptation at the onset of moderate-intensity exercise have been conflicting. Heavy-intensity warm-up exercise has been shown to have no effect on subsequent moderate-intensity V$_{O_2,p}$ exercise kinetics in young adults (11, 22, 24), yet quickened τV$_{O_2,p}$ in older adults (19, 44), reinforcing the assumption that V$_{O_2,p}$ kinetics in the moderate-intensity domain might be age- or at least “V$_{O_2,p$ kinetic dependent” (i.e., related to the initial τV$_{O_2,p$ value; the initial speed of V$_{O_2,p$ adaptation). Indeed, subjects with a poor (slow) initial O$_2$ delivery capacity are most likely to present with shorter τV$_{O_2,p$ after heavy exercise (19, 28, 29, 44). In contrast, Gurd et al. (29) recently reported that prior heavy cycling exercise hastened the V$_{O_2,p$ adaptation, even in young subjects presenting with fast (i.e., <30 s) V$_{O_2,p$ kinetics. However, subjects classified as having “fast V$_{O_2,p$ kinetics” (i.e., 26 s on average) in the study by Gurd et al. had, in fact, rather moderately fast...
kinetics compared with those reported in the literature for moderate exercise [i.e., \( \sim 20 \text{ s} \) (14, 36, 41)]. Thus, whether subjects experiencing very fast VO\(_2\)p kinetics (VFK) [i.e., \(< 16 \text{ s} \), presumably less likely to be limited by O\(_2\) delivery (40)], would respond in a similar fashion, is yet to be investigated. For example, during running exercise, young trained subjects generally present faster VO\(_2\)p kinetics compared with cycling (14, 36). As such, it may be inappropriate to make inferences from the results of priming exercise studies involving cycling vs. running exercises. To date, only one study has investigated the effect of a priming exercise on the VO\(_2\) response following the onset of (high-intensity) treadmill running exercise (33); none has considered the transition to moderate-intensity running exercise in the field.

In an attempt to gain insight into the respective determinants regulating VO\(_2\) at the onset of moderate-intensity, field-running exercise, we sought to simultaneously investigate VO\(_2\)p kinetics, muscular deoxygenation, and estimated Q\(_m\) responses in subjects presenting either moderately fast VO\(_2\)p kinetics (16 s < \( \tau \)VO\(_2\)p < 30 s; MFK) or VFK (\( \tau \)VO\(_2\)p < 16 s), while using a supramaximal “priming exercise” [i.e., repeated sprints (38, 45)] that was likely to improve O\(_2\) delivery (9, 46, 50) and/or to speed muscle oxidative activity (7, 12). We expected that, irrespective of the mechanisms involved (i.e., increased O\(_2\) delivery and/or partial relief in metabolic inertia), VO\(_2\)p kinetics in subjects exhibiting MFK before the warm-up would show a significantly accelerated response after the supramaximal warm-up (19, 28, 29, 44). Conversely, whether subjects exhibiting VFK without warm-up would present a further quickening of VO\(_2\) adaptation after priming was difficult to predict. If the priming supramaximal exercise (SE) had somehow influenced enzymatic control of oxidative phosphorylation, then we would expect the kinetics on the subsequent moderate-intensity exercise bout to be quickened, at least as long as O\(_2\) delivery was not slower than muscle oxidative activity. Conversely, a lack of change in the VO\(_2\)p kinetics in subjects exhibiting VFK without warm-up would suggest that the warm-up did not likely affect metabolic inertia, and/or that O\(_2\) delivery was not likely a critical factor controlling VO\(_2\)p adaptation following exercise onset in these subjects (40). As with other studies (e.g., Refs. 19, 20, 22, 29), we believed that investigation of changes in Q\(_m\) and muscle deoxygenation on submaximal exercise onset following SE would assist with understanding of the mechanisms involved with the control of VO\(_2\)p kinetics.

METHODS

Subjects

Based on the assumption that a 10 ± 5 s difference in the \( \tau \) for the primary phase of the VO\(_2\) response upon initiation of exercise is meaningful (19, 24), we used Minitab 14.1 software (Minitab, Paris, France) to determine that a sample size of at least eight participants would provide a statistical power of 0.8 at an \( \alpha \)-level of 0.05. To further increase the power of our study, we recruited 14 moderately trained athletes (23 ± 4 yr, 77 ± 9 kg, 179 ± 5 cm). All participants were involved (5.1 ± 2.8 h/wk) in run-based sporting activities (running, soccer, handball, or basketball) and had no history or clinical signs of cardiovascular or pulmonary diseases. Participants were not currently taking prescribed medications and presented with normal blood pressure levels and electrocardiographic patterns. The study conformed to the recommendations of the Declaration of Hel-
least 5 s [participants had to be near an additional cone, placed 10–12 m (depending on their running speed) from the starting line; i.e., within 5 ± 1 s]. If adjustment to the required running speed was not satisfactory (i.e., subjects passed a cone outside of a 1-s difference compared with expected time), the test was stopped, and the subject was asked to recommence the test after a 5-min period of passive recovery.

**SE.** The SE test chosen was adapted from previous repeated sprint running tests (6, 45). Before the study, all subjects were familiarized with the repeated-sprint protocol. Subjects performed six repetitions of maximal 25-m sprints, departing every 25 s (Wireless Timing-Radio Controlled, Brower Timing System). During the first ~18 s of recovery between sprints, subjects performed an active running recovery (2.0 m/s). Three seconds before the commencement of each sprint, subjects were asked to assume the ready position and await the start signal. During recovery, audio feedback (i.e., time countdown) was provided so that participants could maintain the required running speed. Participants were instructed to complete all sprints as fast as possible, and strong verbal encouragement was provided to each during all sprints. To assess eventual neuromuscular fatigue, the percentage of speed decrement (%Dec) was calculated for each session (6).

**Measurements**

**Cardiorespiratory measures.** Respiratory gas exchanges and HR were measured during the 30–15, 15–15, Mod1, and Mod2 using an automated breath-by-breath system (K4b2, Cosmed, Rome, Italy) (21). Before each test, the O2 and CO2 analysis systems were calibrated as recommended by the manufacturer. Data were automatically filtered for aberrant data points (i.e., greater than 4 S.D.s from the local mean (39)]. For the 30–15, O2 data were averaged in 20-s increments. Estimated \( \theta_b \) was defined as the \( V_{O2} \) at which \( O_2 \) output began to increase disproportionately in relation to \( V_{O2} \), with a systematic rise in the minute ventilation-to-\( V_{O2} \) ratio and end-tidal \( P_{O2} \), while the minute ventilation-to-\( CO_2 \) output ratio and end-tidal \( PCO_2 \) remained stable. \( V_{O2peak} \) was arbitrarily defined as the highest \( V_{O2} \) values attained during two consecutive 20-s periods (5). A HR peak attained near predicted maximum (220-age), a blood lactate concentration \( ([La]_s) > 8 \) mmol/l, and a respiratory exchange ratio > 1.1 were additionally required to confirm the maximal nature of the test (5).

**NIRS measurements.** The portable NIRS apparatus (Portamon, Artinis, Medical System, Zetten, The Netherlands) used in this study was a two-wavelength, continuous-wave system, which simultaneously used the modified Beer-Lambert and spatially resolved spectroscopy methods. The procedure used to collect data was the same as that used by Van Beekvelt et al. (47) using a similar nonportable device. Changes in tissue oxy-\( Hb \)/myoglobin concentration (oxy-\( Hb \)/Mb), deoxy-\( Hb \)/Mb, and \( \Delta Hb \) were measured using the differences in absorption characteristics of light at 750 and 850 nm. The photodiodes detect changes in the transmission of radiation as a function of time, distance, and wavelength. In the present study, a differential pathlength factor was not determined, but a value of 3.83 was used to allow comparison with previous studies (18, 19, 29). Values for oxy-\( Hb \)/Mb, deoxy-\( Hb \)/Mb, and \( \Delta Hb \), reported as a change from baseline (30-s averaging before each test) in micromolar units (\( \mu M \)) (17), are thus considered as “arbitrary units” throughout this paper. As the deoxy-\( Hb \)/Mb signal can be regarded as being essentially blood volume independent during exercise (15), the method was assumed to be a reliable estimator of changes in intramuscular oxygenation status and \( O_2 \) extraction in the area of interrogation (15, 17). The NIRS probe was positioned on the vastus lateralis muscle of the right leg, ~10 cm from the knee joint and along the vertical axis of the thigh. A surgical marker and a numerical picture were used to mark the probe placement for accurate repositioning during the four trails. The probe and the skin were covered with black tape to prevent contamination from ambient light. Skinfold thickness at the site of application of the NIRS probe was determined before the testing sessions using Harpenden skinfold calipers (British Indicators). The calculated value of skin and subcutaneous tissue thickness was less than one-half the distance between the source and the detector. During all tests, the NIRS system was connected to a personal computer by Bluetooth for data acquisition (10 Hz), analog-to-digital conversion, and subsequent analysis.

**Blood lactate measurement.** Three minutes after the end of each exercise test, a fingertip blood sample (5 \( \mu l \)) was collected, and \( [La]_b \) was determined (Lactate Pro, Arkray). The accuracy of the analyzer was checked before each test using standards. The suitability and reproducibility of this analyzer have been previously established throughout the physiological range of 1.0–18.0 mmol/l (42).

**Data Analysis**

**Assessment of cardiorespiratory kinetics.** \( V_{O2} \) values recorded during the four sets of two moderate-intensity running bouts were automatically filtered for aberrant data points (39), interpolated to 1-s intervals, time-synchronized, and ensemble-averaged to yield two single responses for each subject (i.e., Mod1 and Mod2). \( V_{O2} \) on-transient kinetics were modeled using an iterative technique (Sigmaplot 10, SPSS Science; Chicago, IL) using a monoeponential function (Eq. 1) (39, 48):

\[
V_{O2}(t) = V_{O2b} + A_1 \times [1 - e^{-(t/\tau_{O2})}] \times U_1
\]

where \( U_1 = 0 \), when time \( t \) is less than the time delay 1 (\( \tau_{O2} \)) from the onset of exercise; \( U_1 = 1 \), for \( t \geq \tau_{O2} \); \( V_{O2b} \) is the \( V_{O2} \) before the onset of the rest-to-exercise transition (ml), \( A_1 \) is the asymptomatic amplitude for the exponential term (ml); \( \tau_{O2} \) is the time constant of the exponential (s); and \( \tau_{O2} \) represents the TD for each equation (s). The initial cardiodynamic component was excluded by deleting the first 20 s of data after the onset of exercise, so that the primary component parameters were not distorted by any early cardiodynamic influence (48). Beat-by-beat HR data were filtered for aberrant beats, time-aligned, and averaged to 1-s time bins. These data were then fit from exercise onset with a monoeponential model of the form in Eq. 1.

**NIRS data and assessment of deoxyhemoglobin kinetics.** The NIRS-derived oxy-\( Hb \)/Mb, deoxy-\( Hb \)/Mb, and \( \Delta Hb \) data were time-aligned and ensemble averaged to 1-s time bins to yield two single responses for each subject (i.e., Mod1 and Mod2). As previously proposed (e.g., Ref. 22), the first 90 s of deoxy-\( Hb \)/Mb were modeled using an exponential function of the form given in Eq. 1 to determine the time course of muscle deoxygenation, where deoxy-\( Hb \)/Mb is substituted for \( V_{O2} \). Our choice to analyze the deoxy-\( Hb \)/Mb changes within only the first 90 s was motivated by the monoexponential fitting would likely lead to distortion of the initial TD and the \( \tau \) of the early, primary response of interest. The amplitude of the increase in deoxy-\( Hb \)/Mb from the start to the end of exercise was also calculated. The mean response time (MRT) (deoxy-\( Hb \)/Mb) \( MRT = \text{deoxy-}Hb/\text{Mb} \) TD + \( \tau \) deoxy-\( Hb/\text{Mb} \)) was also calculated to provide a description of the overall time course for muscle deoxygenation. The deoxy-\( Hb \)/Mb and \( \Delta Hb \) signals did not approximate an exponential response, and, as a result, these data were not modeled.

**Muscle capillary blood flow.** One-second time interval \( V_{O2} \) and deoxy-\( Hb/\text{Mb} \) responses were first synchronized using time markers set during each recording (i.e., start of exercise). The \( Q_o \) response to exercise was derived from the kinetics of \( V_{O2} \) and deoxy-\( Hb/\text{Mb} \), as previously proposed by Ferreira et al. (23). The present estimation is based on the fact that \( V_{O2} \) during constant work rate exercise, \( V_{O2} \), has been shown to approximate the \( V_{O2} \) kinetic.
where \( Q_{\dot{m}} \) is substituted for \( V_{\dot{O}_2} \). The response was determined from the MRT (\( Q_{\dot{m}} \) MRT, s), which was
primary component of the \( V_{\dot{O}_2p} \) response). Finally, the time course of variance was found for the fit between modeled and measured \( Q_{\dot{m}} \) data
A double-exponential model was used when a significant gain of exponentially at time zero with the
exponent of the \( V_{\dot{O}_2p} \) determined in response to the transition to moderate-
exercise; thought to be a function of the \( V_{\dot{O}_2m} \)-to-\( Q_{\dot{m}} \) ratio (19, 20). Therefore,
variance was calculated from a weighted sum of the delay and the
Levene test. Possible differences in anthropometric characteristics and
subjects in MFK and VFK groups. Data were very well fitted
The V\(_{\dot{O}_2}\) response during transition from rest to moderate-intensity running exercise without prior high-intensity exercise
(i.e., Mod1, MFK, \( \tau_{V_{\dot{O}_2p}} \) of \( \geq 16 \) s; VFK, \( \tau_{V_{\dot{O}_2p}} \) of \( <16 \) s).
the groups were the same (all \( P > 0.05 \)) with respect to age, stature, body mass, and maximal cardiorespiratory variables, whereas peak [La\(_b\)] was higher in VFK than in MFK (Table 1).
During the entire experimentation, only three subjects (5%) were asked to restart their test (Mod1) because of excessive running speed at the initiation of the run exercise. Their repeated performances were thus included in the final analysis.
As expected, running at 45% \( \dot{V}_{\text{f}}\text{R} \) was just below a moderate-intensity exercise level; mean steady-state \( V_{\dot{O}_2} \) was just below \( \theta_1 \) (60 ± 7 and 59 ± 3% \( V_{\dot{O}_2\text{peak}} \), corresponding to 92 ± 5 and
93 ± 4% of \( \theta_1 \) for MFK and VFK, respectively), and the \( V_{\dot{O}_2p} \) response was well fitted by a monoeXponential function in all cases (see below). During all tests, none of the participants presented with \( V_{\dot{O}_2} \) values higher than that at \( \theta_1 \). Repeated sprint exercises elicited similar cardiorespiratory responses in both groups: 81 ± 10 and 79 ± 8% of \( V_{\dot{O}_2\text{peak}} \) (\( P = 0.42 \)), and
94 and 74 ± 4% of peak HR (\( P = 0.45 \)) in MFK than in VFK, respectively. Mean [La\(_b\)] 3 min after exercise was lower in MFK than in VFK (9.3 ± 1.9 vs. 11.3 ± 0.5 mmol/l; \( P = 0.02 \)). Nevertheless, expressed as percentage of peak [La\(_b\)], [La\(_b\)] was similar in both groups (90 ± 15 vs. 93 ± 12% in MFK and VFK, respectively, \( P = 0.33 \)). The %Dec during the sequence of repeated sprints was similar in both groups (3.3 ± 0.9 vs. 3.4 ± 0.7% in MFK and VFK, respectively, \( P = 0.42 \)).
Table 2 shows the [La\(_b\)] values before and after each moderate exercise bout in both groups. Irrespective of the period considered, there was neither a “group”, nor a “group × repetition” interaction (all \( P > 0.14 \)). There was however, a “repetition” effect for pre- (\( P < 0.001 \)) and postexercise (\( P < 0.001 \) levels. Rating of perceived exertion for moderate exercise showed a repetition effect (\( P = 0.03 \)), but neither a group nor a group × repetition interaction (all \( P > 0.26 \)).
\( V_{\dot{O}_2} \) Kinetics
The \( V_{\dot{O}_2} \) response during transition from rest to moderate-intensity exercise is illustrated in Fig. 2 for two representative subjects in MFK and VFK groups. Data were very well fitted

### Table 1. Characteristics of the participants

<table>
<thead>
<tr>
<th></th>
<th>MFK</th>
<th>VFK</th>
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<tbody>
<tr>
<td>( n )</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Age, yr</td>
<td>23.1 ± 4.5</td>
<td>23.2 ± 3.6</td>
</tr>
<tr>
<td>Stature, cm</td>
<td>180 ± 6</td>
<td>179 ± 5</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>76.1 ± 9.2</td>
<td>78.2 ± 9.8</td>
</tr>
<tr>
<td>( \dot{V}_{\text{f}}\text{R} ), km/h</td>
<td>19.7 ± 0.8</td>
<td>19.5 ± 0.6</td>
</tr>
<tr>
<td>( V_{\dot{O}_2\text{peak}} ), l/min</td>
<td>3.81 ± 0.59</td>
<td>4.00 ± 0.62</td>
</tr>
<tr>
<td>( V_{\dot{O}_2\text{peak}} ), ml·min (^{-1} )·kg (^{-1} )</td>
<td>50.4 ± 7.4</td>
<td>51.2 ± 8.5</td>
</tr>
<tr>
<td>( V_{\dot{O}<em>2} ) at ( V</em>{\text{f}}\text{R} ), %( V_{\dot{O}_2\text{peak}} )</td>
<td>66.5 ± 6.8</td>
<td>67.1 ± 5.4</td>
</tr>
<tr>
<td>( HR_{\text{peak}} ), beats/min</td>
<td>183 ± 8</td>
<td>183 ± 8</td>
</tr>
<tr>
<td>[La(<em>b)] (</em>{\text{peak}} ), mmol/l</td>
<td>10.4 ± 1.7</td>
<td>12.3 ± 1.4*</td>
</tr>
<tr>
<td>RER</td>
<td>1.16 ± 0.1</td>
<td>1.12 ± 0.1</td>
</tr>
<tr>
<td>RPE</td>
<td>8.9 ± 0.7</td>
<td>9.1 ± 0.6</td>
</tr>
</tbody>
</table>

Values are means ± SD of anthropometric characteristics of the participants; \( n \), no. of subjects. Maximal velocity (\( \dot{V}_{\text{f}}\text{R} \)), peak oxygen uptake (\( V_{\dot{O}_2\text{peak}} \), expressed in absolute and relative units), \( V_{\dot{O}_2} \) at the first ventilatory threshold (\( V_{\text{f}}\text{T} \)), peak heart rate (\( HR_{\text{peak}} \)), peak blood lactate ([La\(_b\)] \(_{\text{peak}} \), g/l) exchange ratio (RER), and rating of perceived exertion (RPE) reached during the graded aerobic test in individuals exhibiting moderately fast (MFK) and very fast \( O_2 \) uptake kinetics (VFK) without prior supramaximal warm-up are shown.
using the monoexponential model in all subjects \((r = 0.99 \pm 0.01)\), with a mean 95% CI of \(\tau \pm 2 s\) for both Mod1 and Mod2 respectively. As illustrated in Table 3, there was neither a group nor a repetition effect for \(\dot{V}O_2p\) amplitude and \(\dot{V}O_2p\) TD (all \(P > 0.09\)). For baseline \(\dot{V}O_2p\), there was a repetition effect \((P < 0.001)\), but no group effect \((P = 0.84)\). For \(\dot{V}O_2p\), we observed a repetition effect \((P < 0.01)\), as well as a group \((P < 0.01)\) and repetition \(\times\) group interaction \((P < 0.01)\). Post hoc tests revealed that \(\tau \dot{V}O_2p\) for Mod1 in MFK was longer than values observed for Mod2 in MFK, but also higher than values calculated for Mod1 and Mod2 in VFK (all \(P < 0.01\)). There was, however, no difference between Mod1 and Mod2 in VFK \((P = 1.00)\). There was no significant effect on \(\dot{V}O_2p\) TD (all \(P > 0.19)\). \(\tau \dot{V}O_2p\) for Mod1 and Mod2 were not correlated \([r = 0.39 (-0.18, 0.76), P = 0.19]\). The difference between \(\tau \dot{V}O_2p\) for Mod1 and Mod2 was well correlated to \(\tau \dot{V}O_2p\) for Mod1 \([r = 0.77 (0.40, 0.92, P < 0.01, \text{Fig. 3}],\) but not to \(\tau \dot{V}O_2p\) for Mod2 \([r = -0.29 (-0.71, 0.28), P = 0.34]\). The difference between \(\tau \dot{V}O_2p\) for Mod1 and Mod2 was also well related to [La\(_b\) before Mod2 \([r = -0.68 (-0.89, 0.23, P = 0.01)\)]. There was, however, no relationship between \(\dot{V}O_2p\) peak and \(\tau \dot{V}O_2p\) for Mod1 \([r = -0.01 (-0.54, 0.52, P = 0.96)\) and Mod2 \([r = -0.12 (-0.61, 0.44), P = 0.70)\). The difference between \(\tau \dot{V}O_2p\) for Mod1 and Mod2 was not related to \(\dot{V}O_2p\) peak \([r = 0.07 (-0.48, 0.58), P = 0.82]\).

**HR Kinetics**

HR data are presented in Table 4 and illustrated in Fig. 4 for two representative subjects in MFK and VFK groups. Data were very well fitted using the monoexponential model in all subjects \((r = 0.98 \pm 0.01)\), with a mean 95% CI of \(\tau \pm 2 s\) for Mod1 and Mod2 respectively. We found a repetition effect for baseline HR, HR amplitude, and \(\tau HR\) (all \(P < 0.001)\), but neither a group (all \(P > 0.09)\) nor a group \(\times\) repetition interaction (all \(P > 0.21)\). There was also neither a repetition nor a group effect for HR TD (all \(P > 0.19)\).
Table 4. Heart rate kinetics during the first and second bouts of moderate field running

<table>
<thead>
<tr>
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<th>MFK</th>
<th>VFK</th>
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<tr>
<td></td>
<td>Mod1</td>
<td>Mod2</td>
</tr>
<tr>
<td>Baseline HR, beat/min</td>
<td>79±9</td>
<td>110±13*</td>
</tr>
<tr>
<td>HR amplitude, beat/min</td>
<td>53±10</td>
<td>36±8*</td>
</tr>
<tr>
<td>HR TD, s</td>
<td>1±2</td>
<td>2±3</td>
</tr>
<tr>
<td>tHR, s</td>
<td>18±7</td>
<td>30±10*</td>
</tr>
</tbody>
</table>

Values are means ± SD for baseline, amplitude, TD, and time constant of the primary component for heart rate (tHR) in subjects exhibiting MFK and VFK without prior supramaximal warm-up. *Significant repetition effect (P < 0.05).

Deoxyhemoglobin Kinetics

Figure 5, top, illustrates the profiles of deoxy-[Hb+Mb] during transition from rest to moderate running exercise for two representative subjects in MFK and VFK groups. The deoxy-[Hb+Mb] response, restricted to the first 90 s, was accordingly fitted with a monoexponential model in all subjects (P = 0.99 ± 0.01, with a mean 95% CI of t = 1 ± 2 s for Mod1 and Mod2, respectively). As shown in Table 5, there was neither a group (all P > 0.10) nor repetition (all P > 0.22) effect on baseline oxy-[Hb+Mb], baseline deoxy-[Hb+Mb], deoxy-[Hb+Mb] amplitude, and deoxy-[Hb+Mb] MRT. In contrast, there was a repetition effect for baseline tHb, deoxy-[Hb+Mb] TD, and t deoxy-[Hb+Mb] (all P < 0.001), but neither a group (all P > 0.18) nor a group × repetition interaction (all P > 0.33). The increase in deoxy-[Hb+Mb] within the first 90 s (∆deoxy-[Hb+Mb]), for a given increase in VO₂p (ΔVO₂p), was similar in all subjects and did not change after the SE [i.e., there was neither a repetition (P = 0.70) nor a group effect (P = 0.38)]. Values were 3.5 ± 2.0, 3.3 ± 2.3, 2.9 ± 1.6, and 2.4 ± 1.6 µM·L⁻¹·min⁻¹ for Mod1 and Mod2 in MFK and VFK groups, respectively. Similar results were obtained when considering deoxy-[Hb+Mb] and VO₂p steady-state and end-exercise values.

Estimated Muscle Capillary Blood Flow Kinetics

Normalized Qm profiles during transition from rest to moderate exercise (as a percentage of the final response) are illustrated in Fig. 5, bottom, for two representative subjects in MFK and VFK groups; MRT Qm values are presented in Table 5. Data from Mod2 in MFK, and from both Mod1 and Mod2 in VFK, did not display the two expected phases at the start of exercise (i.e., rapid increase, phase 1, followed by a less pronounced increase, phase 2). Thus responses were fitted with a monoexponential model (r = 0.99 ± 0.01). For Mod1 in the MFK group, visual examination of six subjects’ responses revealed that a biexponential function was more suitable (Fig. 5, bottom left), which was confirmed by a slightly higher goodness of fit (SE of estimate = 0.49 ± 0.09 and r = 0.998 ± 0.001 vs. SE of estimate = 1.3 ± 0.1 and r = 0.999 ± 0.001 for the bi- vs. monoexponential model). Mean 95% CI of kinetics for Qm was mean ± 1 s for both Mod1 and Mod2. There was no effect on Qm TD and overall Qm amplitude (all P > 0.21). Baseline Qm was increased before Mod1 (significant repetition effect, P < 0.001). For Qm MRT, we observed a repetition effect (P = 0.05), as well as a group (P < 0.01) and repetition × group interaction (P < 0.01). Post hoc tests revealed that Qm MRT for Mod1 in MFK were higher than values observed for Mod2 in MFK, but also higher than values calculated for Mod1 and Mod2 in VFK (all P < 0.01). There were significant correlations between Qm MRT and τVO₂p for Mod1 [r = 0.90 (0.71, 0.97), P < 0.001] and Mod2 [r = 0.89 (0.68, 0.96), P < 0.001] (Fig. 6). Difference between τVO₂p for Mod1 and Mod2 was significantly related to MRTQm measured at Mod1 [r = 0.71 (0.29, 0.90), P < 0.01] but not Mod2 [r = −0.19 (−0.65, 0.38), P = 0.53].

DISCUSSION

The aim of the present study was to investigate, for the first time, the effect of a repeated sprint running sequence on VO₂p kinetics, muscular deoxygenation, and estimated Qm responses during transition to moderate-intensity field-running exercise. The main findings were that 1) prior SE quickened the VO₂p kinetics during subsequent moderate-running exercise only in subjects presenting with relatively MFK without warm-up; 2) the magnitude of the speeding of the VO₂p kinetics after heavy-intensity exercise was related to the “lag” in the Qm (and VO₂p) kinetics during moderate-intensity exercise without prior heavy-intensity exercise, with a greater shortening in τVO₂p seen in those individuals with the longer initial Qm MRT; 3) HR and tHb were elevated at baseline before the onset of Mod2 compared with Mod1, suggesting that cardiac output and muscle perfusion were elevated before the onset of Mod2; 4) the TD before muscle deoxygenation was reduced in both
groups during Mod2 compared with Mod1, indicating that the mismatch between local muscle \( \text{O}_2 \) utilization and delivery occurred earlier in the transition to Mod2; and 5) the kinetics of the deoxy-[\( \text{Hb} + \text{Mb} \)] response were slower in Mod2 compared with Mod1 (i.e., longer deoxy-[\( \text{Hb} + \text{Mb} \)] \( \tau \)), but this was adjusted for by the shorter TD, leading to an unchanged overall deoxy-[\( \text{Hb} + \text{Mb} \)] response time.

Use of a Repeated Running Sprint Sequence as a Priming Exercise in the Field

While the practical application of the present study’s protocol is not initially evident (i.e., athletes do not compete at moderate intensities, and older or diseased populations do not perform a preceding high-intensity exercise bout), we chose the exercise intensities in our protocol to allow comparison of participants. Previous observations have shown no differences in the field setting. Previous observations have shown no differences in metabolic [\( \text{Hb} + \text{Mb} \)] and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts (150 s, including recovery periods) repeated running sprints (9, 46, 50) are as effective as a sustained high-intensity submaximal exercise warm-up for speeding the overall \( \dot{V}_\text{O}_2 \) kinetics during a subsequent exercise transition. It is, however, worth noting that, during intense exercise, this faster \( \dot{V}_\text{O}_2 \) response is due predominantly to a marked reduction in the amplitudes of the fast component, with generally no changes shown in the phase II \( \tau \) (9, 12, 50). The short (150 s, including recovery periods) repeated running sprint sequence, used here for the first time, was thus designed to replicate the neuromuscular (i.e., fatigue), metabolic (i.e., marked acidosis), and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts formerly performed in the laboratory (9, 46, 50). These short repeated sprint sequences were used over long duration ones (i.e., 30-s all-out sprints), as they were easier to implement in the field setting. Previous observations have shown no differences in metabolic and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts formerly performed in the laboratory (9, 46, 50). These short repeated sprint sequences were used over long duration ones (i.e., 30-s all-out sprints), as they were easier to implement in the field setting. Previous observations have shown no differences in metabolic and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts formerly performed in the laboratory (9, 46, 50). These short repeated sprint sequences were used over long duration ones (i.e., 30-s all-out sprints), as they were easier to implement in the field setting. Previous observations have shown no differences in metabolic and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts formerly performed in the laboratory (9, 46, 50). These short repeated sprint sequences were used over long duration ones (i.e., 30-s all-out sprints), as they were easier to implement in the field setting. Previous observations have shown no differences in metabolic and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts formerly performed in the laboratory (9, 46, 50). These short repeated sprint sequences were used over long duration ones (i.e., 30-s all-out sprints), as they were easier to implement in the field setting. Previous observations have shown no differences in metabolic and cardiovascular (i.e., elevated cardiac output and \( Q_m \)) effects of the 30-s all-out cycling efforts formerly performed in the laboratory (9, 46, 50).

Table 5. Deoxyhemoglobin and estimated muscle capillary blood flow kinetics during the first and second bouts of moderate-intensity, field-based running

<table>
<thead>
<tr>
<th></th>
<th>MFK</th>
<th>VFK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mod1</td>
<td>Mod2</td>
</tr>
<tr>
<td>Baseline ( \text{oxy-[Hb+Mb]} ), ( \mu \text{M} )</td>
<td>30.7±4.4</td>
<td>34.5±6.2</td>
</tr>
<tr>
<td>Baseline ( \text{Hb} ), ( \mu \text{M} )</td>
<td>53.2±2.9</td>
<td>58.1±4.2*</td>
</tr>
<tr>
<td>Baseline deoxy-[( \text{Hb} + \text{Mb} )], ( \mu \text{M} )</td>
<td>23.5±1.3</td>
<td>23.7±1.6</td>
</tr>
<tr>
<td>End-exercise deoxy-[( \text{Hb} + \text{Mb} )], ( \mu \text{M} )</td>
<td>30.9±1.9</td>
<td>30.1±2.4</td>
</tr>
<tr>
<td>Deoxy-[( \text{Hb} + \text{Mb} )] amplitude, ( \mu \text{M} )</td>
<td>6.3±3.9</td>
<td>5.2±4.0</td>
</tr>
<tr>
<td>Deoxy-[( \text{Hb} + \text{Mb} )] TD, s</td>
<td>15±3</td>
<td>9±2*</td>
</tr>
<tr>
<td>rDeoxy-[( \text{Hb} + \text{Mb} )] , s</td>
<td>8±4</td>
<td>12±7*</td>
</tr>
<tr>
<td>Deoxy-[( \text{Hb} + \text{Mb} )] MRT, s</td>
<td>22±4</td>
<td>21±6</td>
</tr>
<tr>
<td>Baseline ( Q_m ), AU</td>
<td>17.5±8.9</td>
<td>30.2±7.2*</td>
</tr>
<tr>
<td>( Q_m ) TD, s</td>
<td>0±0</td>
<td>0±0</td>
</tr>
<tr>
<td>( Q_m ) MRT, s</td>
<td>17±4</td>
<td>11±4*</td>
</tr>
</tbody>
</table>

Values are means ± SD for baseline, amplitude, TD, and mean response time (MRT) for muscle deoxy-hemoglobin/myoglobin concentration (deoxy-[\( \text{Hb} + \text{Mb} \)]) and muscle blood flow (\( Q_m \)), as well baseline values for oxy-hemoglobin/myoglobin concentration (oxy-[\( \text{Hb} + \text{Mb} \)]) and total hemoglobin (\( \text{Hb} \)) in subjects exhibiting MFK and VFK without prior supramaximal warm-up. *Significant repetition effect (\( P < 0.05 \)). †Significant group effect (\( P < 0.05 \)). Note that near-infrared spectroscopy-derived baseline values are based on a differential pathlength factor of 3.83.
by Gurd et al. (29), our results confirm that, in individuals experiencing exercise onset and neither do interventions such as hyperoxic gas breathing or erythropoietin use (12, 40, 41, 49, 51). Although the shortening of $\tau V_{O2_p}$ in individuals having initially MFK [i.e., subjects presumably more likely to be limited by $O_2$ delivery (40)] could have been related to both an increased bulk of $O_2$ delivery and an accelerated oxidative phosphorylation (i.e., changes in metabolic processes intrinsic to the specific fibers involved, allowed by the faster delivery of other substrates, such as acetyl CoA, ADP, P, NADH, FADH$_2$ after priming exercise), the lack of improvement of $V_{O2_p}$ kinetics in subjects experiencing VFK [i.e., presumably less likely to be limited by $O_2$ delivery (40)] suggests that the heavy warm-up did not affect local factors controlling $O_2$ utilization (i.e., did not reduce the metabolic inertia). Nevertheless, our results suggest that, in individuals having slower $V_{O2_p}$ kinetics, the likelihood of observing a measurable speeding of the response is greater than for those individuals that have relatively faster $V_{O2_p}$ kinetics. Although this lack of a change is likely to be physiologically driven, it is also possible that our inability to measure a “true” reduction in $V_{O2_p}$ may be due to a combination of limited precision in our technology, along with response variability (31).

**Effect of Prior SE on Indexes of Central and Peripheral $O_2$ Delivery**

The marked metabolic acidosis induced by the priming SE probably contributed to an enhanced vasodilatation early in exercise, combined with an acidosis-induced rightward Bohr shift in the oxyhemoglobin dissociation curve, with improved $O_2$ off-loading from Hb after high-intensity exercise (12). However, since intracellular acidosis is known to have a direct inhibitory effect on mitochondrial function (35), blood acidosis in itself cannot be held accountable for the shortening of $V_{O2_p}$ (as shown by the significant correlation between $[La]_b$ before Mod2 and the difference between $V_{O2_p}$ for Mod1 and Mod2 ($r = -0.68, P = 0.01$), but might instead be used as a proxy variable for another process modulating the $V_{O2_p}$ response to exercise [i.e., improved $O_2$ delivery (10)]. Although absolute $[La]_b$ was higher in the VFK group, observation of comparable relative values (i.e., as a percentage of peak blood lactate reached during the maximal graded test, Table 1) suggest that, on an individual basis, subjects from both groups might have benefited to a similar extent from the acidosis. Absolute HR values were significantly elevated before the second exercise bout in both groups, suggesting improved central $O_2$ delivery (Fig. 4). Moreover, HR kinetics, thought to reflect changes in cardiac output [as stroke volume changes minimally with exercise above baseline levels (16)], were similar in the two groups during both moderate-intensity exercise bouts. An elevated local $O_2$ delivery (i.e., a relative hyperemia) was also confirmed in both groups before Mod2 by the greater tHb, reflecting an increased volume of Hb and myoglobin within the field of NIRS interrogation (Table 5). Taken together, these changes likely contributed to the elevated convective $O_2$ delivery to the muscle at the start of the second exercise bout (29).

As previously proposed (22, 23), we estimated $Q_m$ by rearranging the Fick equation and used $V_{O2_p}$ and deoxy-[$Hb+Mb$] as surrogates of $V_{O2_m}$ and arteriovenous $O_2$ difference. Limitations of this technique are known, and estimated $Q_m$ kinetics likely represent the true $Q_m$ kinetics to within...
At the start of Mod2 suggests that local O₂ delivery was a factor involved in the faster V˙O₂p (19, 22, 23, 29) [e.g., deoxy-[Hb+Mb] MRT < 20 s vs. τV˙O₂p > 20 s (22)], the biphasic response of Q˙m is typically evident (23). When considering the present monoeponential-like cases, which are likely to be due to the running exercise associated with the VFK (14, 34), τV˙O₂p was shorter than (or similar to) the deoxy-[Hb+Mb] TD (Table 5). As such, the overall Q˙m response was contained within the first phase of the deoxy-[Hb+Mb] response, and a phase II Q˙m was not apparent. The strong relationship between τV˙O₂p shortening and that of the mean Q˙m response time (r = 0.71, P < 0.01) at the start of Mod2 suggests that local O₂ delivery was a factor possibly contributing to somewhat slower V˙O₂p kinetics during Mod1 in the MFK group. Indeed, with the exception of the Q˙m MRT, which was slower for the MKF group during Mod1 (8.8 ± 1.9 vs. 17.0 ± 3.4 s, P < 0.001), all indirect indexes of central (i.e., HR) and peripheral (i.e., oxy-[Hb+Mb], [Hb]convective O₂ delivery were similar in both groups. Finally, the significant correlations between τV˙O₂p and mean Q˙m response time for both exercises confirm the importance of local blood flow in the control of V˙O₂p kinetics (6). Despite a lack of muscle capillary vasodilatation, differences in intracellular O₂ pressure or insufficiently upregulated sympathetic activity could have been responsible for the observed slower Q˙m without warm-up in the MFK group (40). Further investigation into the muscle hemodynamics and/or bioenergetics is warranted for MFK individuals.

**Effect of Prior Exercise on Muscle Deoxygenation**

At the transition to Mod1, we found similar deoxy-[Hb+Mb] dynamics in both groups (i.e., similar TD, τ, and thus MRT), despite noticeable differences in τV˙O₂p (discussed above). This would suggest that muscle deoxygenation dynamics were not likely directly responsible for the slower V˙O₂p kinetic at exercise onset without warm-up in the MFK group. Conversely, it is probable that the slower Q˙m characterizing these subjects might have limited muscle O₂ delivery, which could, in turn, have slowed V˙O₂m. The similar final deoxy-[Hb+Mb] asymptote value in both groups, as well as a similar Δdeoxy-[Hb+Mb]/ΔV˙O₂p, ratio, was thus consistent with a similar O₂ extraction (i.e., arteriovenous O₂ difference) in all subjects. Associated with the slower Q˙m, this was likely to be responsible for the slower V˙O₂p (and consequently slower V˙O₂p kinetics) in the MFK subjects. Nevertheless, whether V˙O₂m limitations always result in slower Q˙m kinetics and muscle O₂ delivery is uncertain; faster microvascular deoxygenation leading to lower P0₂ may also lead to a possible impairment in diffusive O₂ delivery and, consequently, to slower V˙O₂m.

After SE, a similar shortening of deoxy-[Hb+Mb] TD occurred in both groups, whereas V˙O₂p kinetics were only accelerated in the MFK group. This finding suggests the absence of a relationship between the changes in the response of muscle deoxygenation at exercise onset and those seen for τV˙O₂p (22, 32), as well as an “alteration of the dynamic interaction between V˙O₂m and Q˙m following exercise onset” (22). However, since muscle deoxygenation is generally expected to relate to O₂ utilization along with Q˙m, this particular observation warrants further examination. The faster muscle deoxygenation at exercise onset following high-intensity warm-up has been consistently reported in the literature (19, 22, 29), but has generally been associated with faster V˙O₂p kinetics (1, 18, 29). It is now believed that the deoxy-[Hb+Mb] delay reflects a complex balance between HbMb deoxygenation, O₂ delivery, and the effect of the muscle pump on microvascular volume. As suggested by DeLorey et al. (17), it is thus possible that V˙O₂m is actually increased during the delay, and any increase in deoxy-[Hb+Mb] might be “masked” by other factors, which impact on the volume of Hb in the field of NIRS interrogation. The shortening of the deoxy-[Hb+Mb] TD might, therefore, reasonably account for a faster and/or greater activation of muscle O₂ utilization relative to the increase in local Q˙m at exercise onset. It is possible that the prior exercise affected metabolic pathways and substrates for oxidative phosphorylation, so that these probably contributed to the more rapid adaptation of deoxy-[Hb+Mb]. DeLorey et al. (18) propose that the observation of a slower rate of deoxy-[Hb+Mb] adaptation in conjunction with a shorter phase II τ provide evidence that an O₂ delivery limitation in the control condition would have been alleviated by priming exercise. Indeed, it is apparent that improved blood flow redistribution and local muscle perfusion consequent to prior SE contributed to the slower deoxy-[Hb+Mb] response seen in both groups during Mod2. However, as observed by Ferreira et al. (22), the shortening of the deoxy-[Hb+Mb] TD was adjusted for by the longer τ deoxy-[Hb+Mb], so that the mean deoxy-[Hb+Mb] response time was not affected by prior exercise. In the MFK group, despite no change in mean deoxy-[Hb+Mb] response time, the higher Q˙m observed after warm-up was presumably responsible for the faster V˙O₂p adaptation. In the VFK group, we can hypothesize that, without change in Q˙m, a faster V˙O₂p response could only have been reached with a shorter deoxy-[Hb+Mb] MRT (1, 18, 29). The lack of a V˙O₂p kinetic change observed in these subjects is thus consistent with the unchanged response in local hemodynamic measures (i.e., similar Q˙m and deoxy-[Hb+Mb] MRT).

To conclude, present results show for first time that local O₂ delivery (i.e., Q˙m) could be a possible factor regulating the V˙O₂p during the onset of moderate-intensity, field-based running exercise. However, up to certain fast V˙O₂ kinetic rates (i.e., <16 s), improvement in O₂ delivery is likely to have no further effect on the V˙O₂m adaptation following moderate-intensity exercise onset.

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