European Journal of Applied Physiology (2019) 119:1819–1828
https://doi.org/10.1007/s00421-019-04171-0

ORIGINAL ARTICLE

Leg- vs arm-cycling repeated sprints with blood flow restriction and systemic hypoxia

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Received: 25 January 2019 / Accepted: 3 June 2019 / Published online: 11 June 2019

Abstract

Purpose The aim was to compare changes in peripheral and cerebral oxygenation, as well as metabolic and performance responses during conditions of blood flow restriction (BFR, bilateral vascular occlusion at 0% vs. 45% of resting pulse elimination pressure) and systemic hypoxia (~ 400 m, F_IO_2 20.9% vs. ~ 3800 m normobaric hypoxia, F_IO_2 13.1 ± 0.1%) during repeated sprint tests to exhaustion (RST) between leg- and arm-cycling exercises.

Methods Seven participants (26.6 ± 2.9 years old; 74.0 ± 13.1 kg; 1.76 ± 0.09 m) performed four sessions of RST (10-s maximal sprints with 20-s recovery until exhaustion) during both leg and arm cycling to measure power output and metabolic equivalents as well as oxygenation (near-infrared spectroscopy) of the muscle tissue and prefrontal cortex.

Results Mean power output was lower in arms than legs (316 ± 118 vs. 543 ± 127 W; $p < 0.001$) and there were no differences between conditions for a given limb. Arms demonstrated greater changes in concentration of deoxyhemoglobin (Δ[HHb], − 9.1 ± 6.1 vs. − 6.5 ± 5.6 µm) and total hemoglobin concentration (Δ[tHb], 15.0 ± 10.8 vs. 11.9 ± 7.9 µm), as well as the absolute maximum tissue saturation index (TSI, 62.0 ± 8.3 vs. 59.3 ± 8.1%) than legs, respectively ($p < 0.001$), demonstrating a greater capacity for oxygen extraction. Further, there were greater changes in tissue blood volume [tHb] during BFR only compared to all other conditions ($p < 0.01$ for all).

Conclusions The combination of BFR and/or hypoxia led to increased changes in [HHb] and [tHb] likely due to greater vascular resistance, to which arms were more responsive than legs.

Keywords Occlusion · BFR · Perfusion pressure · Blood volume · Altitude

Abbreviations

ACSM	American College of Sports Medicine
BFR	Blood flow restriction
ES	Effect size
HHb	Deoxyhemoglobin
NIRS	Near-infrared spectroscopy
O_2Hb	Oxyhemoglobin
RER	Respiratory exchange ratio
RPE	Rate of perceived exertion
RST	Repeated sprint ability test to exhaustion
S_{dec}	Percent decrement in RST
S_{best}	Highest mean power of either of the first two sprints in RST
SpO_2	Pulse oxygen saturation
tHb	Total hemoglobin
TSI	Tissue saturation index
VE	Minute ventilation
VO_2	Maximal oxygen uptake
Δ	Delta change over time

Communicated by I. Mark Olfert.

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Introduction

High oxygen consumption requires both oxygen delivery (convective factor) and oxygen extraction (diffusive factor) (Holmberg 2015), along with high perfusion pressure and corresponding vascular conductance (Calbet and Joyner 2010). These mechanisms are limb dependent. For a given oxygen demand, greater oxygen delivery (i.e., product of blood flow and arterial oxygen content) is observed in arms

than legs, partly giving reason for the relatively higher blood flow in arms (Calbet et al. 2005). Furthermore, exhaustive exercise performed in hypoxia with small muscle mass is associated with higher arterial oxygen content and, therefore, a reduced impact of the Bohr effect, when compared to large muscle mass (Calbet et al. 2009). It is well accepted that arms have lower oxygen extraction than legs (Calbet et al. 2005; Clausen et al. 1973). The reason for this difference is probably related to the amount of muscle tissue, such that when considering total tissue volume, the arms have a smaller fraction of oxygen extraction when compared with the legs (Clausen et al. 1973). The arms have demonstrated a great capacity to improve in peak oxygen consumption with training [~ 10% increase (Clausen et al. 1973); 11.4% increase in arms compared with 7.9% in legs during a 5-min time-trial, and 52% increase in arms and only 6% in legs with Wingate (Zinner et al. 2016); and muscle oxygen consumption (Boushel et al. 2014)] in comparison with the legs. However, it remains practically uncertain how to improve oxygen extraction with training, particularly in the arms (Holmberg 2015).

During systemic hypoxia exposure, the limitation of oxygen availability induces vasodilation to increase blood flow and maintain oxygen delivery to muscle. When an external pressure is applied to the limbs to locally create partial restriction of blood flow (blood flow restriction, BFR), this vascular occlusion or ischemia reduces blood flow by vascular resistance and venous return is considerably diminished (Kaijser et al. 1990). Thus, there are both differing methods (local and systemic) and intrinsic mechanisms (metabolic vasodilation and vascular resistance) by which a hypoxic environment may exist, and in which alterations of vascular conductance and blood flow can be created. Additionally, a condition that combines these methods (hypoxia + BFR) is an innovative approach to further challenge and stimulate the vascular system that has never before been investigated.

It is currently unknown how these conditions of hypoxia, BFR, and hypoxia + BFR affect the legs and the arms, respectively. Additionally, a comparison between legs and arms in these conditions and across the same participants appears novel and valuable for better understanding the regulatory mechanisms when a large vs small muscle mass is exposed to reduced oxygen delivery. As differences exist between the limbs, it is important to consider the underlying mechanisms to devise more efficient exercise methods. As evidenced by elite cross-country skiers, the limits of the body have not yet been reached (Holmberg 2015). It is of interest to understand the different circulatory and vascular stresses placed on the limbs in these conditions (local and systemic hypoxia). In addition, repeated sprint exercise is also demanding for cerebral autoregulation of blood pressure and blood flow (Curtelin et al. 2017). Furthermore, the increase in cerebral deoxygenation that contributes to the impairment of repeated sprint ability has been shown to be reduced in hypoxia (Smith and Billaut 2010). Therefore, the aim of this study was to examine limb differences during leg versus arm cycling while implementing localized and systemic hypoxia regarding metabolic, as well as tissue and cerebral oxygenation changes during exhaustive repeated sprint exercise.

The hypothesis was that arms were expected to be more sensitive to changes in oxygen content in conditions of local ischemia and/or systemic hypoxia than legs. Additionally, it was expected that arms would elicit greater changes in peripheral oxygenation parameters compared to the legs, again since arms are known to have greater relative blood flow than legs. The arms were expected to have greater changes in blood volume than legs and particularly during BFR conditions, likely due to greater vasodilation capacity because of a higher blood flow requirement to maintain oxygen saturation and delivery.

Methods

Ethical approval

Seven healthy and active volunteers were involved in this study (five men and two women; mean ± SD; 26.6 ± 2.9 years old; 74.0 ± 13.1 kg; 1.76 ± 0.09 m; 14.1 ± 4.9% body fat). Participants were required to train at least 4 h per week which included some maximal intensity exercise. Participants were excluded if there were any skeletal or muscular injury in the last 3 months, pain, or any other medical condition which could compromise the results. After being informed of the procedures and risks involved, informed consent was obtained from all individual participants included in the study. The experimental protocol was approved by the Ethical Commission for Human Research (CER-VD 138/15) and performed according with the seventh Declaration of Helsinki (2013). Participants were asked to avoid strenuous activity as well as caffeine or alcohol consumption 24 h before each visit. Further, all visits were standardized at the same time of day with at least 48 h between visits to limit fatigue.

Study design

Participants reported to the laboratory for a total of five sessions first in leg cycling and five sessions for arm cycling (one familiarization and four testing sessions for both leg and arm cycling) to assess responses during a maximal repeated sprint test to exhaustion (RST). The randomized testing visits were performed with two different levels of hypoxia (~ 400 m, F_IO_2 20.9%; ~ 3800 m normobaric hypoxia, F_IO_2 13.1 ± 0.1%); as well as two levels of blood flow restriction,

no BFR (0%) and 45% of the pulse elimination pressure (described in detail below). Sessions were performed in a normobaric hypoxic chamber (ATS Altitude Training, Sydney, Australia) with this level of high altitude to simulate an environment common for mountaineers. These percentages for BFR as well as the resistances for legs and arms were chosen based on pilot testing sessions with repeated sprints to exhaustion across the full range of occlusion levels with critical assessment of set duration, power output, torque factor, pedaling frequency, and perceived effort during both leg and arm cycling (Willis et al. 2018).

Familiarization

Anthropometric data (body height, body mass, and skin fold measurement) were measured as well as completion of the informed consent and health questionnaire [Physical Activity Readiness Questionnaire, PAR-Q & YOU (Physiology 2002)]. An experienced technician assessed skin fold measurements to calculate the percentage of body fat for participants using the seven-site formula from the 2010 ACSM guidelines (Medicine 2014). In addition, skin fold measurements were taken on the biceps brachii and vastus lateralis each session to ensure the near-infrared spectroscopy signal would be unaffected due to change in adipose tissue thickness. Participants donned the BFR cuff (legs: 11 × 85 cm cuff, 10 × 41 cm bladder, SC10D Rapid Version Cuff; arms: custom-made 4 × 70 cm cuff, 3 × 41 bladder; D.E. Hokansson Inc., Bellevue, WA, USA) for measurement of the pulse elimination pressure. Pulse elimination pressure was measured at seated rest by gradually inflating the cuff until the point at which no more arterial blood flow was detected via Doppler ultrasound with a linear probe (L12-5L60N) and EchoWave II 3.4.4 Software (Telemed Medical Systems, Telemed Ltd. Lithuania, Milano, Italy) of the femoral (leg protocol) and brachial (arm protocol) arteries, and was measured two or three times for accuracy, with approximately 2 min between trials (Guano et al. 2010). Participants then took position on an electronically braked cycling ergometer for both leg and arm cycling (Lode Excalibur Sport Ergometer, Lode B.V., The Netherlands), where dimensions were recorded and replicated during subsequent sessions. Participants sat behind and slightly beneath the same ergometer which was mounted on a stand to perform arm cycling. After a 5-min warm-up (legs 1.5 W kg^{-1}, arms 1 W kg^{-1}), participants performed two 10-s maximal sprints with 3 min of active recovery between without BFR. Following an additional 5-min passive recovery, participants were familiarized with the RST with no BFR, as described in detail below. All sprints were performed using the "wingate mode" from the manufacturer with an individually fixed torque factor (legs 0.8 Nm kg^{-1}, arms 0.4 Nm kg^{-1}).

Testing sessions

Figure 1 shows the testing protocol for each session which began with an initial warm-up to normalize the near-infrared spectroscopy (NIRS) (3 min at 50 or 30 W followed by 3 min at 100 or 60 W, for legs and arms, respectively) at a cadence of 85 rpm. Thereafter, a 6-min warm-up was performed with a cadence of 85 rpm (1.5 W·kg^{-1} for legs, 1 W·kg^{-1} for arms). Then approximately 3 min after, two maximal 10-s warm-up sprints were performed (similar to the familiarization session) with 3 min of active recovery between sprints. Measurements of oxygen uptake, pulse oxygen saturation (SpO_2), and near-infrared spectroscopy (NIRS) were obtained during the RST. Following the completion of the test, blood lactate concentration was measured followed by rating of perceived exertion. In BFR conditions, the cuffs were placed bilaterally to the most proximal part of each limb and were inflated 5 s before the RST remaining inflated continuously until the end of the post-RST measures. The S_pO_2 was measured at the earlobe with an oximeter (8000Q2 Sensor, Nonin Medical Inc., Amsterdam, The Netherlands), recorded with one sample every 5 s, and reported as the lowest value of the final minute during the RST. Heart rate was monitored at 1 Hz with a telemetry-based heart rate monitor (Polar RS400, Kempele, Finland) for analysis of a maximum value recorded from the sprints. Rating of perceived exertion (RPE) was evaluated using the Borg scale (6–20) as a perception of effort in both the limbs and the breathing immediately after the RST.

Repeated sprint test

After pedaling at 20 W with a cadence of 85 rpm for 1 min, participants were given a 3, 2, 1 countdown and began the RST of 10 s all-out maximal sprint and 20-s active recovery (1:2 work-to-rest ratio) until volitional exhaustion or task failure [cadence < 70 rpm, similar to (Faiss et al. 2013)]. The ergometer was automatically programed to switch to a resistance of 20 W at the end of each sprint for the 20-s recovery. Participants were instructed to perform each sprint maximally, as hard and fast as possible, and to perform as many sprints as possible. Instruction was given to maintain a similar body position for all sprints for both leg and arm cycling, while standing was allowed when leg cycling. Very strong verbal encouragement was given to participants with no indication of the number of sprints performed. The first two sprints were regulated to obtain at least 95% of the peak power from the best sprint from the two warm-up sprints performed to avoid any pacing strategy.

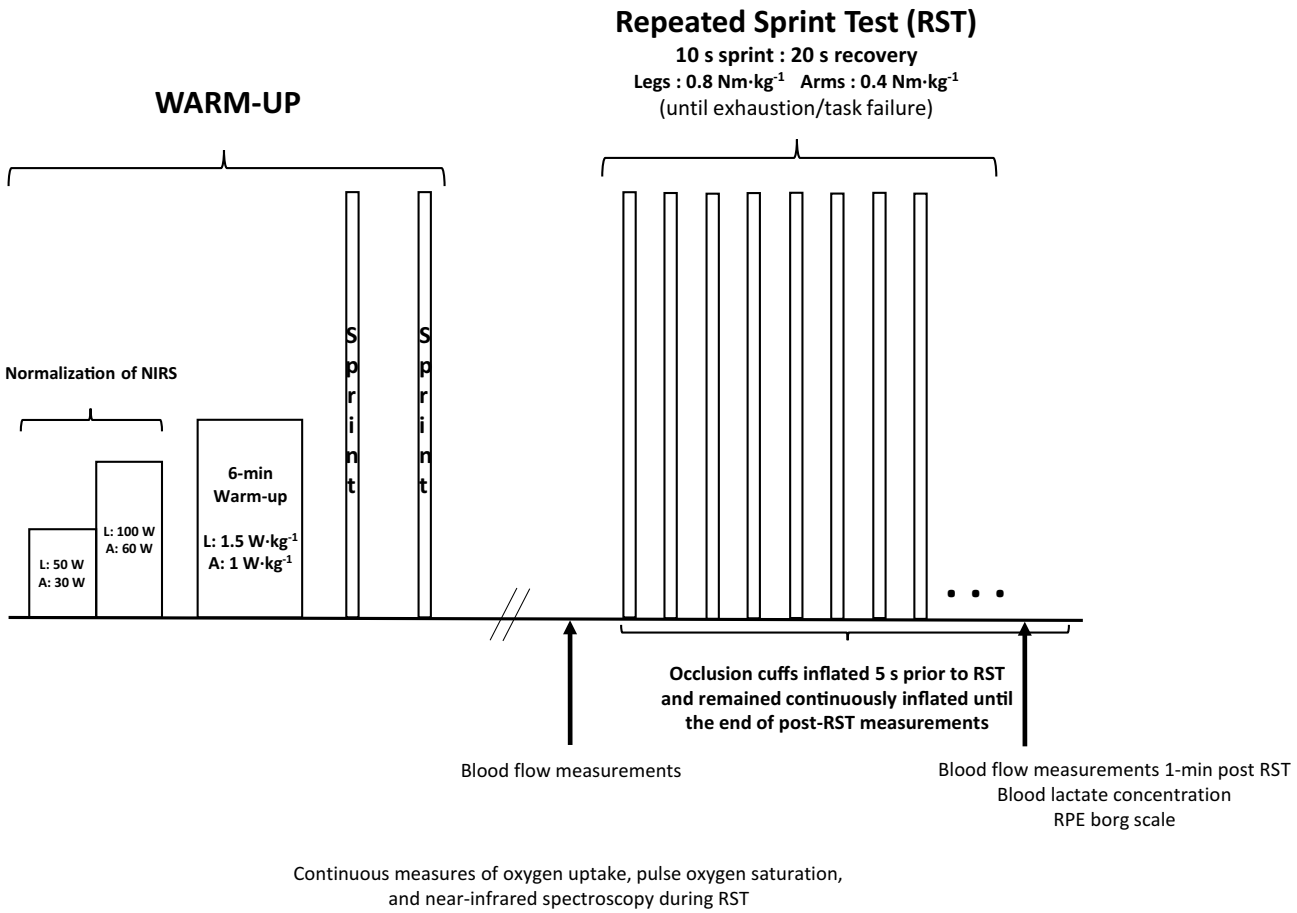

Fig. 1 Experimental protocol

Metabolic measurements

Pulmonary gas exchange was measured continuously breath-by-breath (legs Medgraphics CPX, Loma Linda, CA, USA; arms Quark CPET, Rome, Italy). Oxygen consumption ($\dot{V}O_2$), ventilation ($\dot{V}_E$), respiratory exchange ratio (RER), and respiratory rate (RR) were computed. The systems were calibrated with a 3-L syringe (M9474, Medikro Oy, Finland) and a calibration was made with ambient air and known gas mixtures of O_2 (16%) and CO_2 (5%) prior to each measurement. The highest 30-s average of oxygen uptake was obtained for RST. Doppler blood flow was collected distal to the occlusion on the left femoral artery (leg extended with foot in pedal resting on a standard block) or brachial artery (arm extended resting at ~ 90° shoulder flexion) in the day's condition (if BFR, cuffs inflated 1 min prior) ~5 min pre- and at 1 min post-RST. A 30-s video image was obtained and subsequent analysis was performed with post-RST to take an average of ten frames, essentially a measurement every ~1.5 s. Blood flow was then calculated via a manual measurement of the vessel diameter (mm) using digital calipers and blood velocity (cm s^{-1}). Approximately 3 min after the RST, the earlobe was cleaned and dried, a lancet was used to take a small droplet of blood (0.2 µl) into a strip for analysis of blood lactate concentration (Lactate Scout, EKF Diagnostics, GmbH, Leipzig, Germany).

Performance measurements

Variables of mean power (mean of all sprints, W), number of sprints performed, and total work (kJ) were obtained, in addition to the calculation of percent decrement (S_{dec} (%) = $[1 - (\bar{S}/S_{best})] \times 100$), where $\bar{S}$ corresponds to the mean of all sprints in RST and S_{best} corresponds to the highest mean power of either of the first two sprints in RST (Glaister et al. 2008).

Near-infrared spectroscopy measurements

The PortaMon and PortaLite devices (Artinis, Zetten, The Netherlands), including three light source transmitters (each with two wavelengths of 760 and 850 nm) at 30, 35, and 40 mm distance to the receiver, were used to measure muscle oxygenation of the vastus lateralis and biceps brachii

(PortaMon) and of the prefrontal cortex (PortaLite). Devices were wrapped tightly in transparent plastic to avoid humidity and create a waterproof barrier for proper function and signal quality. The PortaMon was placed on the lower third of the vastus lateralis (leg protocol) and the muscle belly of the biceps brachii (arm protocol) placed parallel to muscle fibers while being attached with double-sided tape, then wrapped with tension against the limb to reduce movement during exercise. The use of a permanent pen was used to mark the position and images were taken to reproduce the placement in subsequent sessions and positioned by the same experimenter each session. The PortaLite was attached on the surface of the left prefrontal cortex using double-sided tape, and placed under a headband to create a dark environment and maintain a stable position of the probe. Measurements included a standard differential path length factor of 4.0 for the vastus lateralis and biceps brachii as there is a lack of any clear standard value during cycling sprints (Faiss et al. 2013) and 6.0 for the prefrontal cortex (Amann et al. 2007; van der Zee et al. 1992). Signals were recorded at the maximum frequency for each device (10 Hz for PortaMon and 50 Hz for PortaLite) and later exported at 10 Hz for further analysis (Oxysoft 3.0.53, Artinis, The Netherlands). A fourth-order low-pass zero-phase Butterworth filter (cutoff frequency 0.2 Hz) was applied during analysis to reduce artifacts and smooth perturbations from pedal strokes (Rodriguez et al. 2018). During RST, the maximum and minimum were detected automatically for each sprint using deoxyhemoglobin as the parameter to determine the visual starting point of the test. This allowed successive sprint and recovery phases to be identified, and sprint phases to be further analyzed. The change (Δ) in concentration for each sprint was calculated as the difference between maximum and minimum values for oxyhemoglobin (Δ[O_2Hb]), deoxyhemoglobin (Δ[HHb]), total hemoglobin (Δ[tHb]). As well, the absolute maximum tissue saturation index (TSI, %) was obtained from each sprint. In addition, data were normalized to the duration of the set to exhaustion, i.e., percentage of sprints performed (i.e., 20, 40, 60, 80, 100%), and a linear interpolation was used to calculate values when there was a fractional number of sprints, as each participant performed a different number of sprints in each condition.

Statistical analysis

Linear mixed effects analysis were performed for the RST to evaluate oxygenation measurements regarding the relationship between fixed effects of limb (legs and arms), condition (400 m, 0%; 400 m, 45%; 3800 m, 0%; 3800 m, 45%), and set duration (20, 40, 60, 80, 100% of sprints performed). Participant was always set as the random effect. The remaining variables (performance and metabolic measurements) were analyzed with a linear mixed model setting limb and condition as the fixed effect. After inspecting residual plots, no obvious deviations from homoscedasticity or normality were present. The rationale for using a linear mixed model was to account for single missing at random data points due to mechanical error and allow for further analysis of remaining data on the same participant. Analyses were performed using R (R Core team 2017, Foundation for Statistical Computing, Vienna, Austria) and nlme4 (Pinheiro 2017). The P values were set to 0.05 and obtained by likelihood ratio tests of the full model with the effect in question against the model without (control). To obtain contrasts, least-squares means for mixed models [library lsmeans (Lenth 2016)] using the Tukey method were computed. Values are represented as mean ± standard deviation unless otherwise noted, and unstandardized effect size (ES) using pooled standard deviations of comparison variables.

Results

Metabolic responses

Power output results along with physiological and metabolic responses are shown in Table 1. Mean power output (316 ± 118 vs. 543 ± 127 W; $p < 0.001$; ES = 1.36) and total work (23 ± 11 vs. 96 ± 73 kJ; $p < 0.001$; ES = 1.15) were 42% and 76% lower in arms than legs, respectively. $\dot{V}O_2$ was reduced with the severity of both hypoxia and BFR (Table 1). SpO_2 (92.7 ± 5.2 vs. 86.2 ± 9.9%; $p < 0.001$; ES = 0.77) was 7.5% greater in the arms than legs over all conditions. Absolute blood flow (mean ± SE, 309 ± 82 vs. 591 ± 240 ml min^{-1}; $p < 0.001$; ES = 0.56) was lower in arms than legs over all conditions and lower in BFR conditions (400 m, 45%: 381 ± 184; 3800 m, 45%: 317 ± 102 ml min^{-1}) than the control (560 ± 227 ml min^{-1}; $p < 0.001$; ES = 0.33 and 0.52, respectively). Further, artery diameter was smaller in arms than legs (4.4 ± 0.7 vs. 5.9 ± 1.7 mm; $p < 0.001$; ES = 1.00).

Oxygenation

With all peripheral NIRS results, Δ[HHb], Δ[tHb], and absolute maximum TSI were greater in the arms than the legs ($p < 0.001$; ES = 0.44, 0.33, and 0.33, respectively) (Fig. 2). An interaction between condition and limb existed with absolute maximum TSI ($p = 0.016$, $F = 5.6$; lower in arms in both 3800 m, 0% and 3800 m, 45% than 400 m, 0% as well as lower in 3800 m, 0% than 400 m, 45%; lower in legs in both 3800 m, 0% and 3800 m, 45% than 400 m, 45%). There were no main effect limb differences for any cerebral NIRS parameters. However, interactions were present between condition and limb for cerebral Δ[HHb] ($p = 0.02$, $F = 5.15$; greater changes in legs in 3800 m, 0% compared

Table 1 Average responses in leg and arm during repeated sprint test to exhaustion (RST) in normoxia with 0% blood flow restriction (BFR), normoxia with 45%, hypoxia with 0%, and hypoxia with 45% conditions

	400 m 0%	400 m 45%	3800 m 0%	3800 m 45%	Limb main effect	Condition main effect	*p*, interaction
Number of sprints							
Legs	31.7 ± 13.5	14.0 ± 6.1[b]	15.9 ± 8.7[b]	8.4 ± 5.7[b,c]		## &&	$p = 0.0002$
Arms	9.9 ± 5.9[a]	8.9 ± 3.6[a]	5.9 ± 1.5[b,c]	6.0 ± 1.4[b,c]	***	†††	$F = 23.1$
Mean power (W)							
Legs	582 ± 125	523 ± 121	549 ± 130	517 ± 148			$p > 0.05$, NS
Arms	338 ± 128	313 ± 122	321 ± 140	292 ± 105	***		
Total work (kJ)							
Legs	183 ± 84	72 ± 28[b]	88 ± 54[b]	42 ± 24[b]		## &&	$p = 0.0002$
Arms	30 ± 13[a]	27 ± 13	17 ± 4[a]	17 ± 4	***	†††	F = 23.1
SpO_2 (%)							
Legs	95.1 ± 3.2	88.0 ± 14.1	78.9 ± 6.3	83.0 ± 7.0		&&& †††	$p > 0.05$, NS
Arms	96.9 ± 3.2	96.9 ± 2.8	88.0 ± 3.2	89.1 ± 3.3	***	§§§ ‡	
Maximal heart rate (bpm)							
Legs	186 ± 7	182 ± 11	179 ± 8	174 ± 11			$p > 0.05$, NS
Arms	172 ± 17	173 ± 17	171 ± 15	169 ± 12	***		
RPE limb (Borg 6–20)							
Legs	17.6 ± 1.9	19.4 ± 0.8	17.0 ± 1.6	18.8 ± 1.5			$p > 0.05$, NS
Arms	18.1 ± 1.5	18.7 ± 0.8	18.1 ± 1.6	18.6 ± 1.2		§§	
RPE breathing (Borg 6–20)							
Legs	18.1 ± 1.5	17.0 ± 1.6	17.9 ± 2.7	18.8 ± 1.5			$p > 0.05$, NS
Arms	15.6 ± 2.0	15.4 ± 1.8	16.4 ± 2.2	16.4 ± 2.3	**		
Blood lactate (mmol L^{-1})							
Legs	8.8 ± 5.8	6.9 ± 2.9	9.4 ± 5.1	8.7 ± 5.1			$p > 0.05$, NS
Arms	9.6 ± 2.3	10.6 ± 3.2	9.5 ± 2.9	8.6 ± 2.7			
VO_2 (mL min^{-1})							
Legs	2978 ± 500	2596 ± 372[b]	2405 ± 370[b]	2185 ± 441[b]		&&& †††	$p < 0.0001$
Arms	2690 ± 416[a]	2768 ± 483[a]	2391 ± 320[a]	2339 ± 280		§§ ‡‡‡	$F = 28.4$
V_E (L min^{-1})							
Legs	149 ± 26	152 ± 33	143 ± 30	143 ± 42			$p > 0.05$, NS
Arms	149 ± 31	149 ± 28	154 ± 34	153 ± 20			
$V_E \cdot VCO_2^{-1}$							
Legs	46 ± 0.4	52 ± 0.4	49 ± 0.3	53 ± 0.4		†††	$p = 0.011$
Arms	56 ± 0.3[a]	54 ± 0.7	62 ± 0.6[a,c]	68 ± 0.7[a,b,c]	***	‡‡	F = 6.4
RER							
Legs	1.09 ± 0.05	1.13 ± 0.10	1.20 ± 0.09	1.23 ± 0.16			$p > 0.05$, NS
Arms	0.99 ± 0.06	1.01 ± 0.08	1.03 ± 0.05	0.98 ± 0.12	***		

Mean ± SD

SpO_2 pulse oxygen saturation, *RPE* rating of perceived exertion, *VO_2* oxygen consumption, *V_E* minute ventilation, *RER* respiratory exchange ratio

[a]($p < 0.05$) significantly different than legs

[b]($p < 0.05$) significantly different than 400 m, 0%

[c]($p < 0.05$) significantly different than 400 m, 45%

***($p < 0.001$), **($p < 0.01$) significant main effect of limb, different between legs and arms

##($p < 0.01$) significant main effect of condition, difference between 400 m, 0% and 400 m, 45%

&&&($p < 0.001$), &&($p < 0.01$) significant main effect of condition, difference between 400 m, 0% and 3800 m, 0%

†††($p < 0.001$) significant main effect of condition, difference between 400 m, 0% and 3800 m, 45%

§§§($p < 0.001$), §§($p < 0.01$) significant main effect of condition, difference between 400 m, 45% and 3800 m, 0%

‡‡‡($p < 0.001$), ‡($p < 0.05$) significant main effect of condition, difference between 400 m, 45% and 3800 m, 45%

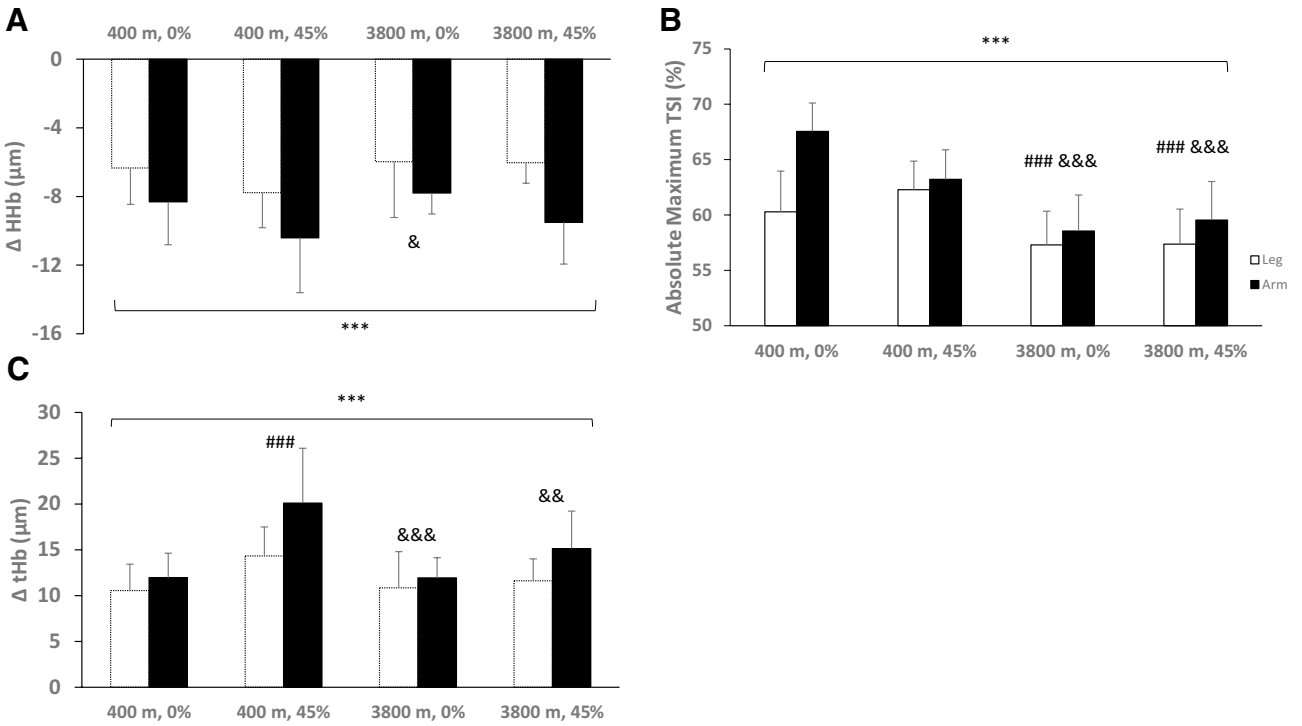

Fig. 2 Near-infrared spectroscopy (NIRS) representing the maximum–minimum delta (Δ) response for the vastus lateralis (leg) or biceps brachii (arm), respectively, during the repeated sprint test to exhaustion (RST). **a** Δ[HHb], **b** absolute maximum TSI, **c** Δ[tHb]. Mean ± SE. ***($p < 0.001$) significant main effect of limb, different between legs and arms; $^{###}$($p < 0.001$) significant main effect of condition, different from 400 m, 0%; $^{\&\&\&}$($p < 0.001$), $^{\&\&}$($p < 0.01$), $^{\&}$($p < 0.05$) significant main effect of condition, different from 400 m, 45%

with both 400 m, 0% and 400 m, 45%; as well as greater changes in legs than arms over all conditions), and for cerebral Δ[tHb] ($p = 0.008$, $F = 7.15$; greater changes in arms in 400 m, 45% than 400 m, 0% as well as greater changes in legs than arms for 400 m, 0% and 3800 m, 0% conditions).

Discussion

The main findings of the present study were: (1) arms elicited greater changes in tissue deoxygenation during RST and were more sensitive to the hypoxia-induced reduction in oxygen supply than legs; (2) the arms demonstrated a greater changes in blood volume than legs, possibly for better maintenance of oxygen delivery via the muscle pump and enhancing perfusion pressure. This suggests greater vascular reactivity of the arms than legs; (3) both the BFR conditions (400 m, 45% and 3800 m, 45%) increased tissue changes in blood volume (Δ[tHb]) likely due to greater vascular resistance, to which the arms were more responsive than the legs; (4) greater cerebral deoxygenation and blood volume were induced in leg versus arm cycling, potentially from the elicited systemic hypoxemia which reduces cerebral oxygen delivery and likely increases oxygen extraction (greater Δ[HHb] and lower TSI) during exercise with large muscle mass.

Arms are more sensitive to the hypoxia-induced reduction in oxygen supply than legs

The arms demonstrated greater changes in tissue deoxygenation during RST (Δ[HHb], Fig. 2) and were more sensitive to the hypoxia-induced reduction in oxygen supply than legs (absolute maximum TSI, Fig. 2. As expected, the SpO_2 was lower in the hypoxic conditions (3800 m, 0% and 3800 m, 45%). Further, the arms had interestingly higher SpO_2 than legs within the hypoxic conditions (Table 1). These results indicated that there are likely differing mechanisms for oxygen transport between the legs and arms, therefore, affecting the regulation of blood flow and oxygen delivery during exercise with altered arterial oxygen content. There is a direct relationship between arterial oxygen content and vasodilation (Calbet 2000). Previous researchers have suggested that there is lower arterial oxygen content and lower muscle blood flow if the maximum pumping capacity of the heart is strained (Calbet et al. 2009), implying that there is higher oxygen extraction when greater amounts of muscle mass are active. Interestingly, in the current study, arms elicited

greater changes in the concentration of deoxyhemoglobin and total hemoglobin, as well as the absolute maximum TSI than legs, likely indicating a greater capacity for oxygen extraction with repeated sprint exercise. When performing exercise at a given workload with small muscle mass (e.g., knee extension or arm cycling, as in the present study), it is known that there is higher oxygen demand than with large muscle mass (e.g., leg cycling). With the arms demonstrating smaller vessel diameter (present results) and lower vascular conductance than legs, this means that perfusion per kg is lower in arms versus legs (Boushel et al. 2011; Calbet et al. 2015). The exercise performance of small muscle mass depends on intrinsic factors for determining the muscle oxygen uptake, as oxygen delivery is very high (Andersen and Saltin 1985; Nielsen et al. 1998; Saltin 1985). Therefore, the current results may suggest that arms have greater sensitivity to oxygenation than legs likely due to smaller muscle mass which requires greater oxygen demand since arms generally have lower tissue oxygen extraction and perfusion.

Greater hyperemic effect in skeletal muscle of the arms vs. legs

The present results suggest a greater hyperemic effect in skeletal muscle of the arms versus legs in the maximal RST exercise, with greater changes in blood volume (Δ[tHb]) (Fig. 2). Researchers have established that blood in any tissue is controlled by perfusion pressure and vascular resistance to blood flow (Delp and Laughlin 1998). Hyperemia in skeletal muscle is related to metabolic vasodilation and increased vascular conductance (i.e., blood flow/mean arterial pressure) from the muscle pump. Increases in blood flow are a result of central cardiovascular and local vascular control mechanisms in addition to the mechanical effects of muscle contraction. This insight gives reasoning to current findings of greater changes in blood volume in arms versus legs. These blood volume concentrations may influence the perfusion pressure along with the activation of the muscle pump to influence the maintenance of oxygen delivery of the arms more so than the legs. Moreover, conduit vessel dilation during dynamic exercise for a given shear rate has been shown to be attenuated in the upper leg (common, deep, superficial femoral arteries) compared with the brachial artery of the arm (Wray et al. 2005). Altogether, this suggests that arms may have greater vascular reactivity than the legs regarding the sensitivity to blood volume.

BFR conditions accentuate vascular regulation of blood flow at a higher rate in arms vs. legs

Furthermore, there was a dramatic increase in blood volume (Δ[tHb]) in both limbs during BFR conditions (400 m, 45% and 3800 m, 45%), demonstrating that BFR conditions accentuate the vascular regulation of blood flow, and at a seemingly much higher rate in the arms than legs. During BFR conditions, there is greater vascular resistance (ratio of mean arterial pressure and blood flow) and, therefore, increased blood volume in the tissue, probably affecting perfusion pressure to thus increase oxygen extraction. As such, these results support early findings demonstrating that ischemic exercise elicits greater oxygen extraction (Pernow et al. 1975). Therefore, it continues to be suggested that the differences in oxygen extraction between limbs (as presently found) may be due to factors involving greater heterogeneity in blood flow distribution (discrepancy of metabolic demand and blood flow supply), lower diffusing areas with arms compared to legs, and the maximal oxidative capacity of the muscle (Calbet et al. 2005).

Greater cerebral deoxygenation and blood volume present in legs vs. arms

Regarding oxygenation in the brain, greater deoxygenation (Δ[HHb]) was demonstrated in both the hypoxic conditions of the legs compared with arms. In hypoxic conditions, especially during intense repeated sprint exercise (Billaut and Smith 2010), systemic hypoxemia contributes to cerebral deoxygenation (Amann and Calbet 2008; Amann and Kayser 2009; Nielsen et al. 2002). In fact, it was suggested in the legs that lower cerebral oxygen delivery initiates an inhibitory reflex and, therefore, the capacity to elevate maximal cardiac output is reduced, thus reducing oxygen delivery to active muscles, peak oxygen uptake, and exercise performance (Calbet et al. 2009). During the present RST, the greater cerebral Δ[HHb] observed in legs than arms seems to confirm this mechanism. This may be related to the greater diffusive limitation in the legs due to a lower gradient of the partial pressure of oxygen in hypoxic conditions (Wagner 1993). Therefore, altogether, these results indicated that the oxygenation of cerebral tissue is highly influenced during exercise with large muscle mass when compared with small muscle mass exercise.

However, there are some limitations of this study that must be considered involving the non-invasive NIRS measurements which should be interpreted with caution, as day-to-day variation in these parameters is around ~ 8–9% (Kishi et al. 2003; Kolb et al. 2004). The small sample size of this study is a limitation emphasizing the need for further investigation.

Conclusion

Interestingly, even though the arms are known generally to extract less oxygen than the legs, the present study demonstrated with maximal repeated sprint exercise that arms

are able to elicit greater changes in oxygenation than legs (greater Δ[HHb] and higher TSI) and thus may produce increases in oxygen extraction to match the higher oxygen demand. In addition, the combination of hypoxia and/or BFR demonstrated greater oxygen extraction as well as greater changes in tissue blood volume (Δ[tHb]) likely due to greater vascular resistance, of which the arms have greater reactivity than legs. This suggests that arms are more responsive or sensitive to changes in oxygenation, specifically the hypoxia-induced reduction in oxygen supply (local or systemic), and likely have a greater capacity to increase oxygen extraction than legs with this type of maximal repeated sprint exercise. Together, this suggests that coaches, athletes, and practitioners should pursue different training protocols between arms and legs. Further, both BFR alone and combined with hypoxia are promising stimuli to challenge vascular adaptation during high-intensity repeated sprint exercise and warrant further research during training studies.

Acknowledgements The authors would like to thank all participants for their efforts, patience, and cooperation with this study.

Author contributions SJW, FB, and GPM conceived and designed research. SJW conducted experiments. SJW and FB analyzed data. SJW, FB, and GPM wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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