Comparisons of muscle oxygenation changes between arm and leg muscles during incremental rowing exercise with near-infrared spectroscopy

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Abstract. Our purpose is to compare the changes in muscle oxygenation in the *vastus lateralis* (VL) and *biceps brachii* (BB) muscles simultaneously using near-infrared spectroscopy (NIRS) during incremental rowing exercise in eight rowers. Based on the BB and VL muscle oxygenation patterns, two points are used to characterize the muscle oxygenation kinetics in both the arm and the leg muscles. The first point is the breaking point (Bp), which refers to an accelerated fall in muscle oxygenation that correlates with the gas exchange threshold (GET). The second point is the leveling-off point (Lo), which suggests the upper limit of O_2 extraction. The GET occurred at 63.3±2.4% of maximal oxygen uptake ($\dot{V}O_{2\,max}$). The Bp appeared at 45.0±3.8% and 55.6±2.4% $\dot{V}O_{2\,max}$ in the BB and VL, respectively. The Lo appeared at 63.6±4.1% and 86.6±1.0% $\dot{V}O_{2\,max}$ in these two muscles, respectively. Both the Bp and the Lo occurred earlier in BB compared with VL. These results suggest that arm muscles have lower oxidative capacity than leg muscles during rowing exercise. The rowers with higher exercise performances showed heavier workloads, as evaluated by Bp and Lo. The monitoring of muscle oxygenation by NIRS in arm and leg muscles during rowing could be a useful guide for evaluation and training. © *2010 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3309741]

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1 Introduction

Comparison of physiological responses between incremental arm and leg exercise is a meaningful way to obtain a clearer understanding of the subject's exercise performance and strategy. Numerous researchers have performed outstanding work on this issue over the past several decades. They found that the maximal oxygen uptake ($\dot{V}O_{2\,max}$) and heart rate (HR_{max}), as well as peak cardiac output attained during incremental arm exercise, were significantly lower than those from incremental leg exercise.[1–3] Some studies showed that the blood lactate threshold (LAT) occurred at lower oxygen uptake during incremental arm exercise compared to incremental leg exercise.[4] The blood lactate concentration was significantly higher in arm exercise than in leg exercise at the same relative exercise intensity.[5] Moreover, lower muscle deoxygenation was observed in *biceps brachii* (BB) muscles during incremental arm cranking compared to that attained in *vastus lateralis* (VL) muscles during incremental leg cycling at all relative exercise intensities.[6] These results implied that exercising arm muscles show poorer oxidative capacity than exercising leg muscles, although the measurements were conducted with either the arm or the leg independently.

Some studies have investigated the interactions of physiological responses between exercising arm and leg muscles. Secher et al. found an increase in leg vascular resistance and a decrease in leg blood flow when arm exercise was added to leg cycling.[7] Richardson et al. found that although an increase in leg noradrenalin spillover was observed when arm cranking was added to leg exercise, the vascular resistance was not increased and the blood flow was not decreased.[8] Volianitis et al. reported that the muscle oxygenation in the BB muscle decreased because of the reduction in the blood flow to the arm when leg cycling was added to arm cranking.[9] Ogata et al. found that both the blood volume and oxygenated hemoglobin decreased in the inactive VL muscle during moderate-intensity arm exercise. However, the decrements of exercising VL muscle were attenuated.[10] All of the preceding experimental results show that the physiological responses of arms and legs interact with each other during exercise. In most sports

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activities, the arm and the leg are involved simultaneously, although with different levels of engagement. For example, leg muscles are more active in biking than in swimming, and the arm muscles are more active in lifting than in rowing. Therefore, it would be useful to have a noninvasive and *in vivo* monitoring system that is able to measure both arm and leg local muscle metabolism simultaneously, as this would allow for an evaluation of the exercise performance of each muscle of interest and identification of the different muscles in use during exercise.

Near-infrared spectroscopy (NIRS) has been broadly used to evaluate trends in local muscle oxygenation and blood volume during exercise[11–13] due to its noninvasive, dynamic, and local measurement capabilities.[14,15] The NIRS signals from the measured muscles mainly reflect the changes in the oxygenated hemoglobin (O_2Hb) and deoxygenated hemoglobin (HHb).[14,16] Based on the muscle oxygenation patterns, two points used to characterize the muscle oxygenation kinetics have been reported during incremental exercise:[17] the breaking point (Bp), which refers to an accelerated fall in muscle oxygenation that correlates with ventilatory or lactate thresholds,[18–20] and the leveling-off point (Lo) related to the leveling-off phase in muscle oxygenation, which suggests an upper limit of O_2 extraction in the local muscle.[21,22] Used to evaluate the balance between muscle O_2 supply and demand, NIRS provides a noninvasive solution to monitor the oxidative metabolism of the arm and leg muscles simultaneously.

To the best of our knowledge, concurrent recordings of oxidative capacity in both the arm and the leg muscles with NIRS measurements have not been conducted. Therefore, the purpose of this study was to compare the oxidative capacities of the BB and VL muscles simultaneously using NIRS during incremental rowing exercise. On the basis of previous NIRS data and related studies that have been conducted in this area, we hypothesized the following: (1) the Bp and Lo points used to characterize the muscle oxygenation kinetics should appear in both the BB and the VL muscles during incremental rowing exercise, and (2) the Bp and Lo points should occur earlier in arm muscles than in leg muscles, suggesting that arm muscles have a lower oxidative capacity than leg muscles when they are coordinated during exercise.

2 Methods

2.1 *Subjects*

Eight collegiate male rowers from a sports institute (Wuhan Institute of Physical Education, China) volunteered to participate in this study. Their average ($\pm$SD) age, height, and body mass were 18.6 ± 1.5 years, 190.0 ± 3.5 cm, and 82.4 ± 10.6 kg, respectively. The thickness of subcutaneous adipose tissue on the surface of each subject's BB and VL muscles was measured before the test, and the mean ($\pm$SD) values were 2.1 ± 0.8 mm and 4.0 ± 0.8 mm, respectively. The experiment was approved by the Human Subjects Research Protection Program of each participating institution. Written informed consent was obtained from every subject before participation, and subjects were allowed to withdraw from the study without any restrictions. All subjects were free from metabolic and cardiorespiratory disorders.

2.2 *Exercise Protocol*

All subjects performed incremental rowing exercise on a rowing ergometer (Concept 2, Inc., Morrisville), the most widely used rowing ergometer for training purposes. The ergometer uses an air-braked resistance mechanism in the form of a flywheel with fans. The flywheel is accelerated with each stroke by pulling on a handle. The harder the subjects pull, the greater the resistance. Each test was initiated with a 150-s rest period while the subject was seated on the ergometer. Then, the subject began to complete a stepwise incremental protocol of 50 W every 180 s until exhaustion or the attainment of two or more of the following end points:[6] (1) age-predicted maximal heart rate (HR), which was calculated as 220-age in years, (2) leveling-off of the $\dot{V}O_2$ (increase of less than 100 $ml \cdot min^{-1}$) with increasing power output, and (3) respiratory exchange ratio (RER) $\geqslant 1.10$. The subjects rowed at their preferred stroke rate. They could monitor the power outputs on the monitor (PM3) of the ergometer and were instructed to keep the power at each workload as constant as possible during the tests.[23]

2.3 *Muscle Oxygenation Measurements*

Muscle oxygenation changes in the BB and VL muscles were measured by a two-probe continuous-wave (CW) NIRS device developed in our laboratory.[24] According to the Beer–Lambert law,[25] the light intensity after absorption and scattering of tissue can be expressed by

$$I = GI_0 \exp[-(\alpha_{HHb} C_{HHb} + \alpha_{O_2Hb} C_{O_2Hb})L], \quad (1)$$

where G is constant attenuation, I_0 is input light power, and α_{HHb} and α_{O_2Hb} are the molar extinction coefficients of HHb and O_2Hb, respectively. C_{HHb} and C_{O_2Hb} are the concentrations of HHb and O_2Hb, respectively, and L is the photon path. Our NIRS device measured only the relative concentration changes in HHb and O_2Hb. Assuming I' as the baseline, the optical density (OD) can be expressed by

$$\mathrm{OD} = \ln \frac{I'}{I} = (\alpha_{HHb} \Delta C_{HHb} + \alpha_{O_2Hb} \Delta C_{O_2Hb})L, \quad (2)$$

where ΔC_{HHb} and ΔC_{O_2Hb} are the relative concentration changes in HbO_2 and Hb from the baseline. Light at the 730-nm wavelength is mainly absorbed by HHb when it penetrates the tissue, while at the 850-nm wavelength, the main absorption chromophore is O_2Hb. The 805-nm wavelength is the isosbestic point of the absorption coefficients of O_2Hb and HHb. The light intensity changes of 805 nm could be used to calculate the concentration changes in total hemoglobin (tHb), which is considered the blood volume index. We choose 16, 16, and 15 cm as the photon paths for 730, 805, and 850 nm, respectively.[25] Using the known molar extinction coefficients of HHb and O_2Hb at these three wavelengths in Eq. (2), the relative concentration changes in HHb, O_2Hb, and blood volume can be obtained.

One probe of the CW NIRS device was firmly attached on the motor point of the right VL muscle, approximately 14 to 18 cm above the knee, parallel to the major axis of the thigh, while the other probe was placed on the motor point of the medial aspect of the right BB muscle, approximately

6 to 8 cm from the elbow crease.[6] Each probe consisted of one light source (Epitex, Japan) and one detector (OPT101, Burr–Brown). The light source integrated three light-emitting diodes (LEDs) with wavelengths of 730, 805, and 850 nm in a TO18 package. Those LEDs were switched sequentially by a timing controller circuit. The detector was 3 cm from the light source in order to collect the diffusely back-reflected photons from 1.5 to 2.0-cm-deep tissue.[25] Most of the collected photons penetrated the measured muscle, because the subjects had little subcutaneous adipose tissue on the surface of the measured muscles, as mentioned earlier.

The NIRS signals were collected at a sampling frequency of 2.9 Hz. The difference between the relative concentration changes in O_2Hb and HHb ($\Delta[O_2Hb\text{-}HHb]$) was taken as the muscle oxygenation index.[19,22,26] Average relative concentration changes in total hemoglobin ($\Delta[tHb]$) and $\Delta[O_2Hb\text{-}HHb]$ values attained from BB and VL muscles were calculated at rest and during the last 30 s of each workload.[19] All data were expressed in arbitrary units (a.u.) with resting values set at 0. The characteristic points of muscle oxygenation index, breaking point (Bp) and leveling-off point (Lo) were determined by three experienced investigators, who reviewed the NIRS measurements from each subject independently. The recorded resting values were not considered. The values of the characteristic points were retained when at least two investigators were in agreement.

2.4 *Cardiorespiratory Measurements*

The respiratory gas exchange parameters, such as minute ventilation ($\dot{V}e$), oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and respiratory exchange ratio (RER), were monitored by a metabolic system (MAX II, Physio-Dyne Instrument Corp., New York) during the experiment. The oxygen and carbon dioxide sensors in the instrument were calibrated using known precision gases (100% nitrogen for the low calibration process; 21% oxygen, 5% carbon dioxide, and the balance as nitrogen for the high calibration process) according to the instruction manual of the instrument. The volume of the mass flow sensor was calibrated using a 3-l syringe. The heart rate (HR) was recorded using a heart-rate detector that is a part of the MAX II, and the signals were received in the form of output pulses of a polar transmitter and receiver. The data for respiratory gas exchange and HR were averaged every 30 s.$\dot{V}O_{2\,max}$ was defined as the maximal $\dot{V}O_2$ observed during each test. The gas exchange threshold (GET) was identified by the ventilatory equivalent method: GET was the breaking point at which there was an increase in the ventilatory equivalents for oxygen ($\dot{V}e/\dot{V}O_2$) versus time without a simultaneous increase in the ventilatory equivalents for carbon dioxide ($\dot{V}e/\dot{V}CO_2$) versus time.[22,27] The breaking point was evaluated visually by three investigators independently, and it was identified when at least two investigators were in agreement. We also used the V-slope method to identify the GET automatically with a computer to confirm the GET identified by the ventilatory equivalent method.[28,29]

2.5 *Statistical Analysis*

All data were expressed as means ± SE unless indicated otherwise. One-way repeated measure ANOVA was used to compare the cardiorespiratory data at GET and the points of muscle oxygenation in the measured muscles. The relationship between the time corresponding to the appearances of GET and the characteristic points of muscle oxygenation was assessed using Pearson's product-moment correlation. The level of significance was set at $P < 0.05$. All statistical analyses were performed using SPSS computer programs.

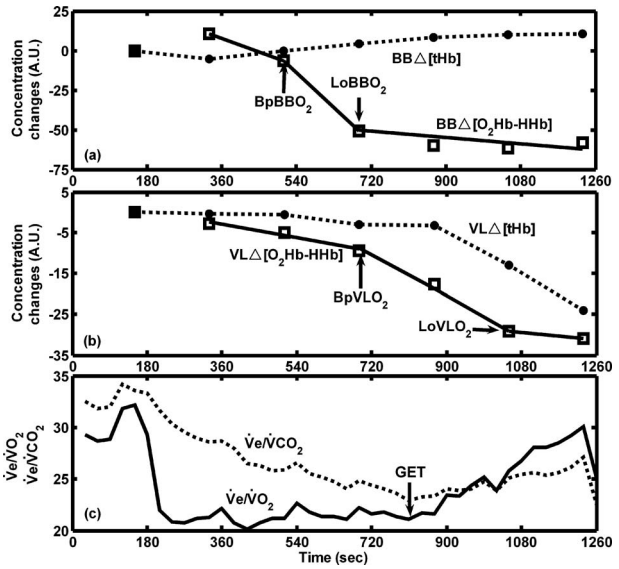

Fig. 1 A typical example of the kinetics of muscle oxygenation in (a) the BB and (b) the VL. (c) $\dot{V}e/\dot{V}O_2$ and $\dot{V}e/\dot{V}CO_2$ versus time profile for one rower (subject 5). The NIRS signals were expressed in arbitrary units (a.u.), as resting values were set at 0. BBΔ[tHb] and VLΔ[tHb] (●) represent the changes in blood volume in the BB and VL; BB$\Delta[O_2Hb\text{-}HHb]$ and VL$\Delta[O_2Hb\text{-}HHb]$ (□) represent the changes in muscle oxygenation in the BB and VL; $BpBBO_2$ and $BpVLO_2$ represent the breaking points (Bps) in the BB and VL muscle, respectively, from which an accelerated fall in muscle oxygenation was observed; and $LoBBO_2$ and $LoVLO_2$ represent the leveling-off points (Lo) in the BB and VL muscle, respectively, from which a leveling-off phase in muscle oxygenation was shown. $\dot{V}e/\dot{V}O_2$, ventilatory equivalent for O_2; $\dot{V}e/\dot{V}CO_2$, ventilatory equivalent for CO_2; and GET, gas exchange threshold.

3 Results

The subjects were numbered from 1 to 8 according to their best 2000-m rowing competition results. Figure 1 shows the typical results of muscle oxygenation kinetics measured by NIRS in BB [Fig. 1(a)], VL [Fig. 1(b)], and $\dot{V}e/\dot{V}O_2$ and $\dot{V}e/\dot{V}CO_2$ versus time profile [Fig. 1(c)] for one rower (subject 5) during an incremental rowing test. An accelerated decrease in the muscle oxygenation index of the BB ($BB\Delta[O_2Hb\text{-}HHb]$) was observed from the breaking point called $BpBBO_2$, as illustrated in Fig. 1(a). A similar accelerated fall in the muscle oxygenation index of the VL ($VL\Delta[O_2Hb\text{-}HHb]$) was also found from the breaking point $BpVLO_2$, as shown in Fig. 1(b). These two characteristic points of muscle oxygenation in BB and VL were found in all eight subjects' results. As shown in Fig. 1, muscle oxygenation began to level off from the second characteristic point, the leveling-off point (Lo), called $LoBBO_2$ and $LoVLO_2$ in

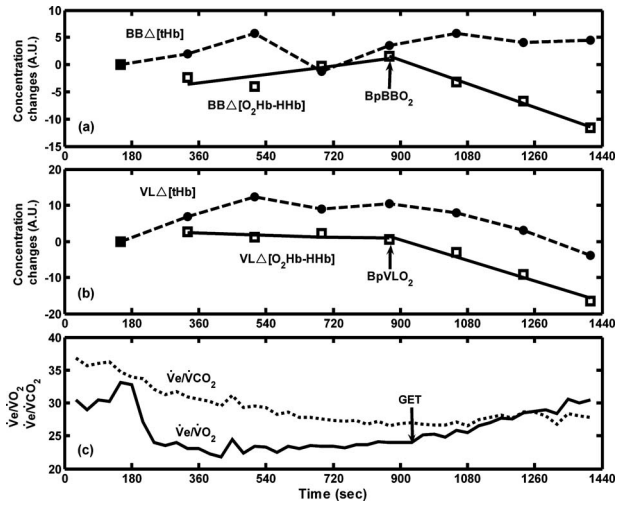

Fig. 2 Typical muscle oxygenation changes of subjects with high exercise performance (subject 1) who did not show a leveling-off phase in the muscle oxygenation index. Values were expressed in arbitrary units (a.u.), as resting values were set at 0. BBΔ[tHb] and VLΔ[tHb] (●) are the changes in blood volume in the BB and VL, respectively; BBΔ[O_2Hb-HHb] and VLΔ[O_2Hb-HHb] (□) are the changes in muscle oxygenation in the BB and VL, respectively; $BpBBO_2$ and $BpVLO_2$ are the breaking points (Bps) in the BB and VL muscle oxygenation, respectively. $\dot{V}e/\dot{V}O_2$, ventilatory equivalent for O_2; $\dot{V}e/\dot{V}CO_2$, ventilatory equivalent for CO_2; and GET, gas exchange threshold.

the BB and VL, respectively. Five subjects (subjects 4 to 8) showed leveling-off phases in both the BB and the VL muscles during incremental exercise.

Three rowers with higher exercise performance (subjects 1 to 3) did not show the leveling-off phases in their BB and VL muscle oxygenation indices in this study. The typical muscle oxygenation kinetics of these elite athletes (subject 1) are illustrated in Fig. 2. The muscle oxygenation indices decreased sharply from $BpBBO_2$ and $BpVLO_2$ to the end of the exercise in the BB and VL muscles. Similar tendencies in BB and VL muscle oxygenation were also observed in subjects 2 and 3.

The pertinent cardiorespiratory responses during incremental rowing tests are shown in Table 1. $BpBBO_2$ ($\sim 622.5 \pm 7.5$ s, $45.0 \pm 3.8\% \dot{V}O_{2\,max}$) occurred earlier than $BpVLO_2$ ($\sim 735.0 \pm 56.4$ s, $55.6 \pm 2.4\% \dot{V}O_{2\,max}$), and both appeared earlier than GET ($\sim 813.8 \pm 54.4$ s, $63.3 \pm 2.4\% \dot{V}O_{2\,max}$). The physiological responses are significantly different among these three points. Significant correlations were found between the time at which $BpBBO_2$ and GET appeared ($r=0.81$, $P<0.05$) and the time corresponding to $BpVLO_2$ and GET occurrences ($r=0.98$, $P<0.01$). $LoBBO_2$ ($\sim 762 \pm 72.0$ s, $63.6 \pm 4.1\% \dot{V}O_{2\,max}$) appeared earlier than $LoVLO_2$ ($\sim 1014 \pm 67.4$ s, $86.6 \pm 1.0\% \dot{V}O_{2\,max}$), and the physiological responses corresponding to these two points are significantly different. No significant correlation was found between the time corresponding to $LoBBO_2$ and $LoVLO_2$ ($P>0.05$). The maximal cardiorespiratory and metabolic data reached by the subjects are also shown in Table 1.

Table 1 Cardiorespiratory responses corresponding to the breaking points (Bps) of an accelerated fall in BB muscle oxygenation ($BpBBO_2$) and VL muscle oxygenation ($BpVLO_2$), to the gas exchange threshold (GET), to the leveling-off points in the BB muscle oxygenation ($LoBBO_2$) and the VL muscle oxygenation ($LoVLO_2$), and to maximal exercise (Max).

Parameters	$BpBBO_2$	$BpVLO_2$	GET	$LoBBO_2$	$LoVLO_2$	Max
Time (s)	622.5±7.5	735.0±56.4*	813.8±54.4*§	762±72.0	1014±67.4 #	1275±56.4
$\dot{V}O_2$ (L/min)	2.29±0.25	2.73±0.23*	3.18±0.24*§	2.89±0.33	3.96±0.28 #	5.03±0.25
$\dot{V}O_2$ (ml/min/kg)	28.0±2.1	33.7±1.9*	39.8±1.9*§	38.8±3.5	53.3±2.0 #	62.3±0.9
$\dot{V}CO_2$ (L/min)	1.98±0.24	2.48±0.21*	2.91±0.21*§	2.75±0.31	4.25±0.23 #	5.64±0.26
$\dot{V}e$ (L/min)	51.4±5.8	62.7±4.8*	74.6±5.5*§	70.6±6.6	111.8±1.8 #	161.4±5.7
$\dot{V}e/\dot{V}O_2$	22.7±1.01	23.12±0.62	23.55±0.55	24.78±1.44	28.72±1.92	32.82±1.47
$\dot{V}e/\dot{V}CO_2$	26.23±0.81	25.63±0.73	25.50±0.74	25.93±1.16	26.62±1.50	28.85±0.95
RER	0.87±0.02	0.91±0.01*	0.93±0.01*§	0.96±0.03	1.07±0.03 #	1.16±0.03
HR (beats/min)	130±5	140±3*	153±2*§	142±8	170±3 #	185±3
Percentage of $\dot{V}O_{2\,max}$ (%)	45.0±3.8	55.6±2.4	63.3±2.4	63.6±4.1	86.6±1.0	

Note: Values are means±SE. $\dot{V}O_2$, oxygen uptake; $\dot{V}O_{2\,max}$, the maximal oxygen uptake; $\dot{V}CO_2$, carbon dioxide output; $\dot{V}e$, minute ventilation; RER, respiratory exchange ratio; and HR, heart rate. * indicates significantly different from $BpBBO_2$ ($P<0.05$). § indicates significantly different from $BpVLO_2$ ($P<0.05$). There are significant differences among cardiorespiratory parameters at $BpBBO_2$, $BpVLO_2$, and GET ($P<0.05$). # indicates significant difference between $LoBBO_2$ and $LoVLO_2$ ($P<0.05$).

Table 2 The power outputs (POs) attained at Bp, GET, and Lo points and the maximal power outputs (PO_{max}) and oxygen uptake ($\dot{V}O_{2\,max}$) obtained by all subjects.

Subject	PO at $BpBBO_2$ (W)	PO at $BpVLO_2$ (W)	PO at GET (W)	PO at $LoBBO_2$ (W)	PO at $LoVLO_2$ (W)	PO_{max} (W)	$\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$)	2000-m rowing performance (s)
1	250	250	250	—	—	350	5896	442
2	250	250	250	—	—	350	5551	451
3	200	250	250	—	—	350	5589	460
4	200	250	250	300	350	350	5404	465
5	150	200	200	200	300	300	4854	486
6	150	200	200	200	300	300	4767	495
7	150	150	150	200	250	250	4302	513
8	100	150	150	200	250	250	3896	542

Note: The subjects were numbered from 1 to 8 according to their best 2000-m rowing performances. $BpBBO_2$ and $BpVLO_2$, the breaking points (Bps) of accelerated fall in the BB and VL muscle oxygenation, respectively; GET, gas exchange threshold; and $LoBBO_2$ and $LoVLO_2$, the leveling-off points (Lo) in the BB and VL muscle oxygenation, respectively.

The maximal power outputs (PO_{max}), the maximal oxygen uptakes ($\dot{V}O_{2\,max}$), and the power outputs (POs) attained at GET, Bp, and Lo points by the subjects are shown in Table 2. The subjects with higher exercise performances reached higher $\dot{V}O_{2\,max}$, heavier PO_{max}, and heavier POs at Bp and Lo points in both the BB and the VL muscles. Significant correlations were found between $\dot{V}O_{2\,max}$ and PO attained at Bp (PO at $BpBBO_2$ versus $\dot{V}O_{2\,max}$: $r=0.94$, $P<0.01$; PO at $BpVLO_2$ versus $\dot{V}O_{2\,max}$: $r=0.97$, $P<0.01$) and between PO_{max} and $\dot{V}O_{2\,max}$ (PO_{max} versus $\dot{V}O_{2\,max}$: $r=0.97$, $P<0.01$).

4 Discussion

This is the first study to compare the acute changes in muscle oxygenation and blood volume of the VL and BB muscles simultaneously using NIRS during incremental rowing exercise in well-trained rowers. We found two characteristic points in each muscle during incremental tests: the breaking point (Bp), which refers to an accelerated fall in muscle oxygenation that correlates with the gas exchange threshold (GET), and a leveling-off point (Lo) in muscle oxygenation, which implies the near maximal oxygenation extraction in these subjects. Both the Bp and the Lo points appeared earlier in the BB muscle than in the VL muscle.

Our endurance-trained rowers have little subcutaneous adipose on the surface of the measured muscles, so most of the NIRS signals detected came from the measured muscles, and the adipose tissue did not affect the related trends in muscle oxygenation.[30] The nature of CW NIRS measurement is still qualitative,[16,30] mainly due to the unknown scattering coefficient of the measured tissue.[31] The subcutaneous adipose tissue at the surface of the muscle, which influences the light penetration path length, also greatly affects the quantitative measurements by CW NIRS. Therefore, we used arbitrary units (a.u.) in our study with resting values set at 0, and we focused only on the characteristic points of muscle oxygenation kinetics (breaking point and leveling-off point), which can be used reliably in any subject.[22]

Some studies reported that $\Delta[O_2Hb\text{-}HHb]$ can be influenced by the changes in blood volume ($\Delta[tHb]$), so they used $\Delta[HHb]$ as the muscle oxygenation index.[32–34] However, other studies did not report this influence.[17,22,35,36] In the design of our homemade CW NIRS device, the $\Delta[O_2Hb\text{-}HHb]$ is calculated from the difference between OD 850 and OD 730, while the tHb is calculated from OD of 805 nm. The changes in blood volume could not be influenced by the changes in OD 850 and OD 730. Thus, there is almost no cross talk between the blood volume and oxygenation changes.[25] In fact, the $\Delta[O_2Hb\text{-}HHb]$ and $\Delta[HHb]$ also showed the same characteristic points in our study (unpublished data), which is in agreement with previous studies.[22] Therefore, $\Delta[O_2Hb\text{-}HHb]$ was chosen as the muscle oxygenation index in this study.

In this study, GET was evaluated visually by three investigators independently according to the ventilatory equivalent method. However, this method is sometimes inaccurate due to its reliance on ventilatory response.[28,29] It is difficult to identify the GET using this method in some subjects due to insensitive ventilatory chemoreceptors, e.g., obstructive lung disease, or even in some normal subjects. We also sometimes experienced difficulty in identifying the GET in this study. As shown in Fig. 1(c), although $\dot{V}e/\dot{V}CO_2$ showed a slight increase from where the arrow indicated, two investigators still experientially chose this point as the GET because $\dot{V}e/\dot{V}O_2$ began to systematically increase at this point. Therefore, we also used the V-slope method to identify the GET automatically with a computer (unpublished data) to confirm the GET identified by the subjective ventilatory equivalent method. We

found that the GET identified by the ventilatory equivalent method occurred at $63.3 \pm 2.4\%$ $\dot{V}O_{2\,max}$, while the GET identified by the V-slope method occurred at $62.8 \pm 2.0\%$ $\dot{V}O_{2\,max}$. Significant correlation was found between the GET identified by these two methods according to their occurrence time ($r=0.994$, $P<0.01$). Actually, the GET identified by these two methods occurred at the same time point in six subjects (subjects 1 to 6), while only two subjects (subjects 7 and 8) showed a different GET, with only about a 30-s time lag. Since it is difficult to show the results of the V-slope method with time as the x axis, we presented the results of the ventilatory equivalent method here.

4.1 *Characteristic Points in the BB and VL Muscles*

The breaking points (Bps) of muscle oxygenation kinetics, called $BpBBO_2$ and $BpVLO_2$ in the BB muscle and the VL muscle, respectively, were found in every subject. Both the $BpBBO_2$ and the $BpVLO_2$ occurred earlier than the GET in this study. NIRS measures local blood deoxygenation of the measured tissue, and GET is identified by the respiratory gas exchange measurements. The time lag between Bp obtained by NIRS and GET from the whole body may be explained by the local versus systemic apparatuses.

To meet the ATP requirements at high work intensity, more glycolytic muscle fibers will be recruited, which will lead to the accumulation of lactic acid in the local exercising muscles. Lactic acid can dissociate into lactate and H^+. A previous study has demonstrated an accumulation in the H^+ concentration (H^+ threshold) in the local exercising muscle. The H^+ threshold is correlated with classic metabolic thresholds during incremental exercise and could be identified by NIRS measurements.[37] The accumulated H^+ in the local muscle will increase the oxyhemoglobin dissociation via the Bohr effect and consequently accelerate the decrease in muscle oxygenation.[17] The accumulated H^+ will also be transported out of the muscle and be buffered by bicarbonate or other buffers in the systemic blood, resulting in the production of carbonic or other acids. The carbonic acid will dissociate into water and carbon dioxide, resulting in an increase in arterial CO_2 tension. The increased CO_2 tension will stimulate the central chemoreceptors and cause a nonlinear increase in gas exchange.[17,18] These steps may result in delayed reaction between the local muscle H^+ accumulation and the increase in gas exchange.

The Bp point in VL muscle appeared to be close to the GET, which was consistent with previous studies.[17,20] However, the Bp point in the BB muscle was not close enough to call it "near GET." $BpBBO_2$ appeared earlier than $BpVLO_2$. Previous studies have reported that the BB has a lower percentage of oxidative muscle fiber than the VL.[38,39] The recruitment of more glycolytic muscle fibers to meet the ATP requirements during incremental exercise should occur earlier in the BB muscle than in the VL muscle. Skeletal muscle is the major producer of lactic acid, but its oxidative fibers are also the primary consumers of lactic acid.[40–42] The muscle capacity for lactic acid clearance will be enhanced by a predominance of oxidative muscle fibers.[41] Thus, the accumulation of lactic acid would occur later in the VL muscle than in the BB muscle. The earlier Bp points in BB muscles should be attributed to the lower oxidative capacity of arm muscles, owing to the lower percentage of oxidative muscle fibers.

A leveling-off point (Lo) was found in five of the subjects (subjects 4 to 8), suggesting that the upper limit of O_2 extraction was attained in these subjects.[17,21] The earlier occurrence of Lo in the BB muscle might suggest that "peak" O_2 extraction capacity was reached earlier for BB exercise. The differences in maximal arm and leg O_2 extraction might be attributed to the physical properties of the exercising muscles, such as the muscle mass or the percentage of slow twitch oxidative muscle fibers.[39] Moreover, it is evident that the blood volume began to decrease in the VL muscle and seemed to level off in the BB muscle, as shown in Fig. 1. This might suggest that the leveling off in muscle oxygenation could be due to limited oxygen availability in these muscles. In addition, because the use of the arm and leg muscles can be different in different athletes, we cannot rule out other possibilities due to the small number of statistics samples.

4.2 *Comparisons among the Subjects*

Previous studies have found that most of the energy needed for 2000-m rowing was derived from oxidative metabolism, so the rowers with higher oxidative capacity usually showed a better rowing competition performance.[43,44] The exercise performances of rowers are correlated with their maximal power outputs (PO_{max}) and $\dot{V}O_{2\,max}$ attained during incremental exercise.[23,45] In this study, significant correlation was also found between PO_{max} and $\dot{V}O_{2\,max}$ ($r=0.97$, $P<0.01$).

Significant correlations were found between $\dot{V}O_{2\,max}$ and power outputs (POs) attained at Bp in our study (PO at $BpBBO_2$ versus $\dot{V}O_{2\,max}$: $r=0.94$, $P<0.01$; PO at $BpVLO_2$ versus $\dot{V}O_{2\,max}$: $r=0.97$, $P<0.01$). The correlations between PO attained at Lo and $\dot{V}O_{2\,max}$ were not evaluated due to the small number of the statistics samples. However, it is still evident that the rowers with higher exercise performance attained heavier workload intensities at Lo points, as shown in Table 2. It is believed that endurance training would improve the oxidative capacity of muscles by improving their capacity for lactic acid utilization and clearance.[41] Thus, it is reasonable that the well-trained rowers with higher exercise performances could attain heavier power outputs at both the Bp and the Lo points.

The subjects in this study are all endurance rowers. They have been trained regularly on the rowing ergometer and were able to keep the power output as constant as possible at each step during the experiments. The maximal cardiorespiratory metabolic data, the PO_{max}, and the PO attained at GET are consistent with previous studies.[23,46] Some studies reported that the results of a performance test on the rowing ergometer between rowers and nonrowers had to be considered separately because specific muscle mass and oxidative capacity of working muscles might be increased by specific training.[46,47] It is unclear whether the untrained subjects will still show earlier Bp and Lo points in arm muscles compared with leg muscles, and this is an interesting question in need of further study.

5 Conclusion

The oxidative capacities of the BB and VL muscles were compared using NIRS during incremental rowing exercise in this study. The breaking point (Bp) and leveling-off point (Lo) used to characterize the muscle oxygenation kinetics were found in both the BB and the VL muscles. The Bp and Lo points occurred earlier in arm muscles than in leg muscles, suggesting that arm muscles showed lower oxidative capacities than leg muscles during incremental rowing exercise. This coincided with the results of previous studies about the oxidative exercise capacities of rowers, in which the arm and leg exercises were recorded separately.[3] Moreover, rowers with higher exercise performances attained heavier workload intensities at the Bp and Lo points in both the BB and the VL muscles. The monitoring of muscle oxygenation by NIRS in arm and leg muscles during rowing might provide a new and useful means to evaluate an athlete's training regimen.

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