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Oxygen supply-consumption balance in the thigh muscles during exhausting knee-extension exercise

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Abstract. The purpose of this study was to investigate the difference in muscle oxygenation between the individual muscles involved in an exhaustive knee-extension exercise. Eight active women performed exercise by extending the knee joint from 90° to 30° (60 extensions min^{-1}) at 20%, 30%, and 40% maximum voluntary contraction (MVC). Changes in oxy-(ΔHbO_2), deoxy-(ΔHb), and total (ΔHbT) hemoglobin concentrations, and oxygen saturation ($\Delta SO_{2NIRS} = HbO_2/HbT$) in the vastus lateralis (VL) and rectus femoris (RF) muscles were measured with a spatially resolved near-infrared spectrometer (NIRS). The ΔSO_{2NIRS} in the VL and RF decreased rapidly from the pre-exercise control value (VL: 75.6±0.9%; RF: 81.6 ±1.6%) at the onset of exercise at three different intensities, although no significant difference in ΔSO_{2NIRS} was found between the two muscles at this time. However, the ΔSO_{2NIRS} decreased more rapidly thereafter and reached a lower value at exhaustion in the VL than in the RF. The difference in ΔSO_{2NIRS} between the VL (−10.3±1.7%) and RF (−4.0±1.0%) was significant ($p<0.05$) when exercise intensity was 30% MVC. When the decreases in ΔHbO_2 and ΔHbT ($p<0.05$) were compared at different exercise intensities, the values at 30% and 40% MVC were significantly lower (ΔHbO_2: $p<0.01$; ΔHbT: $p<0.05$) than those at 20% MVC in the VL, but there was no significant difference in any of the parameters in the RF, or in ΔHb in the VL. These results suggest that the muscle oxidative response to exhaustive knee-extension exercise differed between the VL and RF muscles. At exhaustion, oxygen saturation decreased to a lower level in the VL than in the RF, and an intensity-dependent difference in muscle oxygenation parameters was observed at 30% MVC in the VL but not in the RF muscles. [S1083-3668(00)01201-6]

Keywords: deoxygenation; tissue oxygen saturation; synergistic muscles; exercise intensity.

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1 Introduction

The relative importance of the oxygen supply to the muscles and oxygen utilization in the muscle tissue is the subject of debate in graded exercise.[1–3] Oxygen delivery limitation versus oxygen utilization limitation is a key issue in determining maximal oxygen uptake of muscles. Oxygen consumption of the knee muscles increases in close relation to an increase in blood flow during submaximal exercise at constant load,[4] suggesting that the oxygen supply-consumption balance is not only intensity dependent but also time dependent.

In previous studies, oxygen consumption was estimated in whole limbs which consist of several muscle groups. However, a nonuniform contribution of each muscle to the whole limb exercise was demonstrated in the forearm muscles by near-infrared spectroscopy (NIRS),[5] and in the quadriceps muscles by surface mechano-myogram (MMG),[6] from the viewpoint of muscle oxygenation and mechanical activity. These studies were concerned with exercise at different intensities, but no information is available on time-dependent changes in the oxygen supply-consumption balance of synergistic muscles exercised to exhaustion.

The purpose of this study, therefore, was to clarify the difference in muscle oxygenation among the individual muscle groups recruited in an exhaustive knee-extension exercise. For this purpose, spatially resolved NIRS was used, and tissue oxygen saturation was estimated in the vastus lat-

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eralis (VL) and rectus femoris (RF) muscles during exercise at different intensities.

2 Methods

2.1 Subjects

Eight physically active women participated in this study after giving their informed consent. Their mean (±SD) age, height, and body mass were 21.0±0.9 years, 159.7±4.1 cm, and 55.0±5.0 kg, respectively.

2.2 Experimental Procedure

The dynamic knee-extension exercise was performed at three different intensities until exhaustion at a frequency of 60 extensions min^{-1}. The subjects extended their right knee joint from 90° to 30°, the fully extended position was defined as 0°. The intensities corresponded to 20%, 30%, and 40% of maximum voluntary contraction (MVC).

2.3 Measurement

The NIRS probe was placed over the VL and RF muscles at the thickest site of each muscle. The tissue thickness over these positions, measured by ultrasonography (Echo Camera SSD-500; Aloka CO, Tokyo, Japan), was 26.6±1.6 (VL) and 25.6±1.4 mm (RF) for muscle, and 9.1±0.8 (VL) and 10.6 ±0.8 mm (RF) for the subcutaneous adipose tissue (VL vs RF; $p=0.058$), respectively.

The changes in the concentrations of oxygenated hemoglobin (ΔHbO_2), deoxygenated hemoglobin (ΔHb), and total hemoglobin ($\Delta HbT:HbO_2+Hb$) were determined with a spatially resolved NIRS (OM100AS or OM200; Shimadzu Co., Japan). The NIRS signals at wavelengths of 780, 805, and 830 nm were used for the OM100AS, and those at 690, 780, 805, and 830 nm were used for the OM200. Two detectors were placed over the VL or RF at distances of 2.5 and 4.0 cm from the light source. The oxygen saturation of the tissue (ΔSO_{2NIRS}) was calculated as the ratio of HbO_2:HbT. Measurements in the VL and RF at each intensity were performed on different days, separated by at least 1 day. The same protocol was repeated to measure ΔSO_{2NIRS} at two places, over the VL or RF.

2.4 Statistics

Two-way analysis of variance with repeated measures was employed to determine the effects of exercise time and different muscle groups on ΔSO_{2NIRS}. If a significant difference was obtained, one-way analysis of variance was used with Fisher's PLSD *post hoc* comparison. Differences in ΔHbO_2, ΔHb, and ΔHbT (changes from pre-exercise control values) at exhaustion after exercise at different intensities were evaluated by one-way ANOVA with *post hoc* comparison of Fisher's PLSD. Differences at $p<0.05$ were considered to be significant. The data are expressed as means±SE, unless indicated otherwise.

3 Results

Exercise time until exhaustion was 362±68, 110±18, and 51±7 s at 20%, 30%, and 40% MVC, respectively. Figure 1 shows a typical example of the time trend of ΔSO_{2NIRS} in the VL and RF muscles. ΔSO_{2NIRS} decreased rapidly at the onset of exercise at three intensities in both muscles and reached a steady level or recovered towards the pre-exercise baseline. To compare the ΔSO_{2NIRS} between the VL and RF, the values of each subject were averaged every 10 s: the mean value of the eight subjects is shown in Fig. 2. For the first 20 s, ΔSO_{2NIRS} decreased steeply with no significant difference between the two muscles. However, ΔSO_{2NIRS} decreased more rapidly thereafter and reached a lower value at exhaustion in the VL than in the RF, although at 30% MVC it increased gradually by 2.5±1.4% until exhaustion in the RF. This increase was significant ($p<0.05$) when compared with the mean value obtained during 20–30 s of exercise. The difference between ΔSO_{2NIRS} in the VL (−10.3±1.7%) and RF (−4.0±1.0%) was significant ($p<0.05$) when the exercise intensity was 30% MVC.

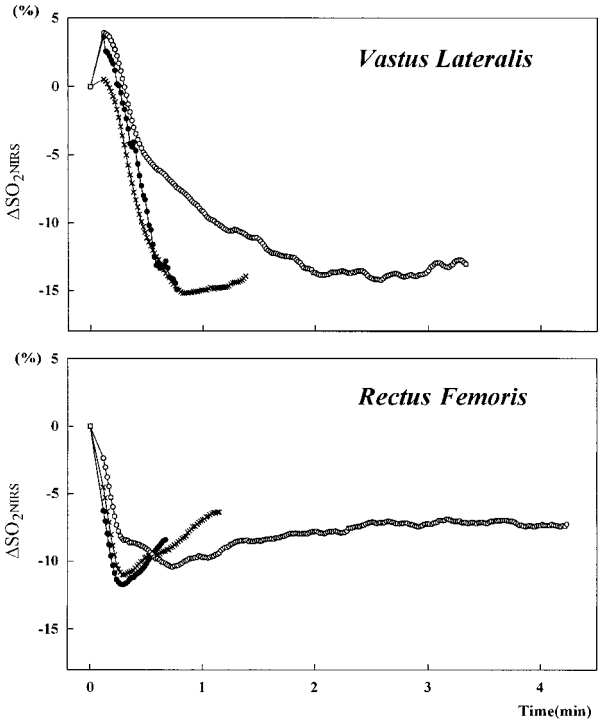

Fig. 1 Typical example of ΔSO_{2NIRS} during exercise continued to exhaustion in the VL (upper) and RF (lower) muscles. The exercise intensities were 20% (○), 30% (×) and 40% (●) MVC. The data were obtained at 1 Hz and are expressed as changes from the pre-exercise control value.

At exhaustion, ΔSO_{2NIRS} in the VL and RF at 30% and 40% (VL: −13.3±1.9; RF: −9.0±1.6%) MVC exercise was significantly lower (VL: $p<0.01$; RF: $p<0.05$) than that at 20% MVC (VL: −7.4±2.0%; RF: −4.3±2.0%).

ΔHbO_2, ΔHb, and ΔHbT, which determine ΔSO_{2NIRS}, were compared in the two muscles at exhaustion (Figure 3). ΔHbO_2 ($p<0.01$) and ΔHbT ($p<0.05$) in the VL decreased significantly during exercise at 30% and 40% MVC, compared to 20% MVC. However, no significant differences were found in any of the parameters in the RF, or ΔHb in the VL muscles.

4 Discussion

The present study demonstrated that ΔSO_{2NIRS} declined steeply for the first 20 s, although no significant difference in

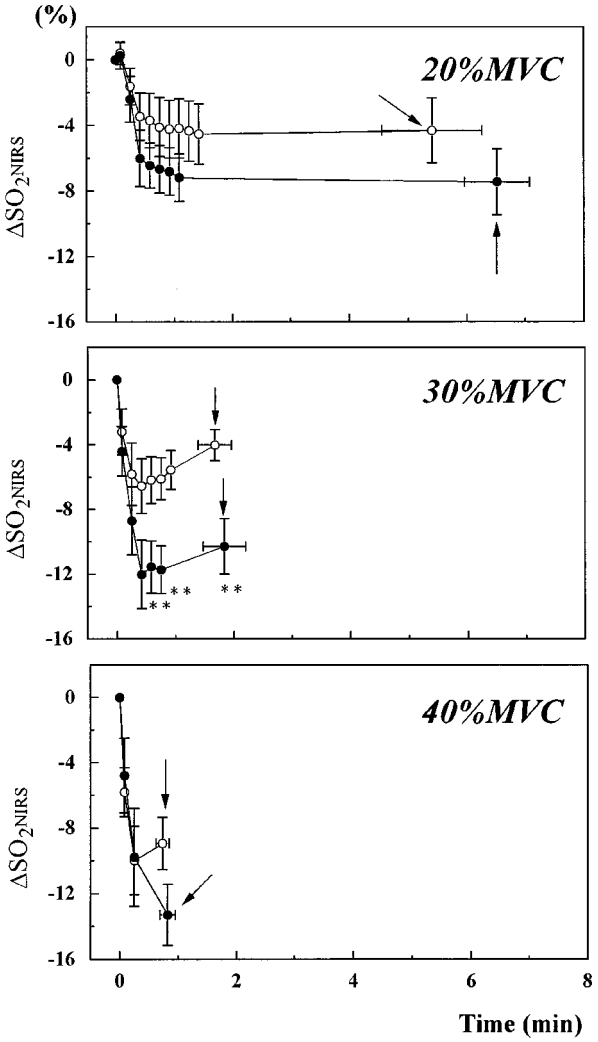

Fig. 2 Changes in ΔSO_{2NIRS} during exercise continued to exhaustion in the VL (●) and RF (○) muscles. ΔSO_2 obtained at 1 Hz was averaged every 10 s until one of the subjects discontinued exercise due to fatigue and the last 10 s before exhaustion. The values are expressed as changes from the pre-exercise control value. **: $p<0.01$ between the VL and RF. ↓: exhaustion point.

this parameter was found between the VL and RF during this period. After 20 s, ΔSO_{2NIRS} continued to decrease in the VL and reached a lower level than in the RF. The NIRS signals have been thought to reflect oxygenation of hemoglobin and myoglobin at the level of the capillaries and veins,[7] and NIRS can detect different muscle oxygenation profiles,[8] although a further study is needed to identify the more restricted origin of NIRS signals.[9,10] Thus, the rapid reduction in ΔSO_{2NIRS} in the present study suggests that desaturation of hemoglobin/myoglobin was accelerated up to 20 s in the thigh muscles. This is consistent with the results of direct measurements (^{1}H NMR) of myoglobin desaturation in the thigh muscles during knee-extension exercise.[10] In addition, the present study indicates that the rate of deoxygenation in the VL and RF muscles did not differ significantly during the initial period of exercise. However, during the latter period of exercise the magnitude of deoxygenation became larger in the VL than in the RF, and the difference between both muscles reached statistical significance during exercise at 30% MVC.

At exhaustion, there was no significant intensity-dependent difference in any of the measurements obtained from the RF muscles, whereas in the VL the changes in ΔHbO_2 and ΔHbT were significantly larger at the higher intensities (30% and 40% MVC) than at the lower intensity (20% MVC), with a similar change in ΔHb. These results suggest that the VL and RF muscles showed a different muscle oxygenation response as the intensity of the knee-extension exercise increased. One possible explanation would be a difference in the contribution of these two muscles to force generation in the knee-extension exercise.[11] However, according to Kouzaki et al.[6] the RF muscle seemed to be susceptible to fatigue within the quadriceps muscle during fatiguing activity estimated by MMG. Therefore, the most probable explanation for the different oxygen saturation in the VL and RF would be different metabolic properties of the muscle groups,[12,13] due to their different fiber type composition.[14] The VL muscle was reported to be more abundant in type I fibers than the RF,[14] and could be active even when tissue oxygenation decreased more than in other muscles with fewer type I fibers.

Another change that should be taken into consideration is the blood flow into individual muscles. Andersen and Saltin[15] reported that blood flow in the leg during knee-extension exercise increased with exercise intensity, and suggested that hyperemia at low work intensities was due to vasodilation. In contrast, oxygen supply to the active muscle, which is determined by blood flow, was found to level off at higher exercise intensity in the forearm muscles during handgrip exercise when monitored by NIRS.[16] With regard to time-dependent changes, Vøllestad et al.[4] reported that blood flow in the leg increased gradually with increasing leg oxygen consumption during submaximal knee-extension exercise. In the present study, the blood flow to individual muscles of the thigh was not measured and remains to be studied further. The only information obtained in this study related to blood volume changes (ΔHbT), which differed between the two muscles, showing a larger decrease in the VL. This nonuniformity in the blood volume change is consistent with the results obtained from the forearm synergistic muscles during handgrip exercise.[5] As the subcutaneous fat thickness would influence the absorbance of NIRS signals[17] and might affect the ΔSO_{2NIRS} data, the difference in subcutaneous adipose thickness between the different sites studied should be taken into consideration. However, in this study the difference in subcutaneous adipose tissue thickness over the VL and RF was not statistically significant.

In conclusion, the muscle oxidative response to exhaustive knee-extension exercise differed between the VL and RF; oxygen saturation decreased to a lower level in the VL than in the RF, and intensity-dependent differences in muscle oxygenation parameters were observed at 30% MVC in the VL but not in the RF.

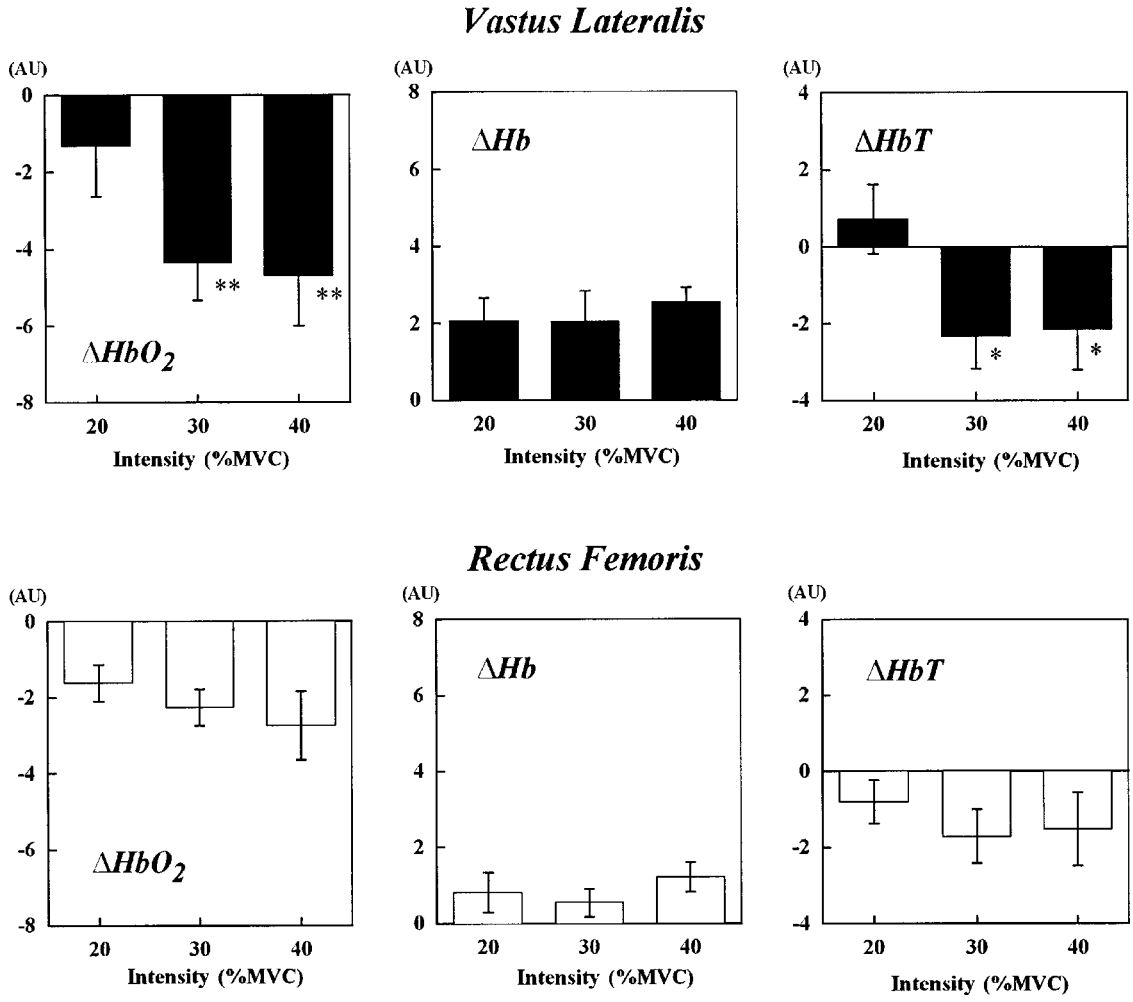

Fig. 3 Mean ΔHbO_2, ΔHb, and ΔHbT at exhaustion in the VL (upper) and RF (lower) muscles in eight subjects. The values are expressed as changes from the pre-exercise control value. AU: arbitrary unit. *: $p<0.05$ and **$p<0.01$ compared to 20% MVC.

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