Oxygenation and Blood Volume in Skeletal Muscle in Response to External Force

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Abstract. Oxygenation and blood volume in skeletal muscle have been used to evaluate muscle contraction force. This paper aims to reveal the correlations between local oxygenation, blood volume and external force. Eight subjects performed isometric elbow flexion exercise of different force levels and isokinetic elbow exercise. In isometric exercise, oxygenation and blood volume indices were significantly correlated with joint torques; and their relationships could be described by linear equations. Compared with the oxygenation rate, the change of blood volume between rest and muscle contraction was more suitable to evaluate static muscle contraction force than oxygenation. In isokinetic exercise, blood volume demonstrated obvious periodicity in different motion cycles, and had low correlations with joint moments. Oxygenation indices demonstrated obvious differences between the five motion cycles. In conclusion, blood volume was found to be suitable to estimate the static and dynamic muscle contraction force, and validate musculoskeletal system biomechanical model.

Keywords: oxygenation, blood volume, near-infrared spectroscopy, isometric exercise, isokinetic exercise.

1 Introduction

Oxygen of skeletal muscle tissue is combined with hemoglobin(Hb) and myoglobin(Mb) in blood and muscle cells[1]. Near-infrared spectroscopy (NIRS) is a noninvasive method to determine local oxygenation and blood volume in skeletal muscle and brain. It was firstly used to study oxygen metabolizing of brain in 1977[2]. It is based on the relative transparency of the tissue for light in the near-infrared region and the oxygen-dependent absorption changes of Hb and Mb[3]. The reliability of NIRS has been well established. Significant correlations were observed for oxygenation and blood volume in muscles during two trials of static muscle endurance tests in healthy males[4]. NIRS can directly measure the content of oxygenated Hb/Mb(C_{oxy}), deoxygenated Hb/Mb(C_{deoxy}), total Hb/Mb($C_{Hb/Mb}$), and tissue oxygen saturation(TSI).

Oxygen of skeletal muscle have been used in evaluating muscle contraction force, validating biomechanical model. Modeling human musculoskeletal system is a sustaining research focus. Because of complexity of the model, it needs variety of methods to validate it. The muscle oxygenation and blood volume, which can

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measured by NIRS, were common used indices for evaluating muscle tissue activities and workload. There is growing interest in studying oxygenation and blood volume in response to exercise and external force. The oxygenation of muscle, which can be calculated by the change rate of $C_{oxy}(V_{oxy})$, C_{deoxy} (V_{deoxy}), and $TSI(V_{TSI})$, reflect muscle oxygen consumption situation. When muscles contract, HbO_2 and MbO_2 deoxygenated into HHb and HMb. The lager muscles contract force, the faster muscles consume oxygen. Praagman[5] reported that the change rate of HbO_2/MbO_2 is linearly related to external force in isometric elbow exercise. The relationship between V_{oxy} and external force can sufficiently be described by a linear equation. The blood volume, which can be represented by the content of Hb, reflects muscle contraction situation. Blood is extruded out of capillary vessels when muscle contracts. The content of Hb can't be measured by NIRS. But the change of $Hb(\Delta_{Hb})$ is mostly equal to the change of Hb/Mb, because the content of Mb in muscle cells is steady. Jgensen[6] reported that muscular contraction between 20% and 75% of MVC reduced or occlude erector spinae muscle blood flow.

It has been proved that the oxygenation and blood volume indices are notably correlation with joint moments in isometric movement. However, there are few comparative studies about different muscle oxygen indicators in correlation with joint moments. And it is lack of assessment in dynamic muscle contraction force. This research carried out isometric elbow flexion exercise under different force levels and isokinetic elbow exercise. Then the correlations of V_{oxy}, V_{deoxy}, V_{TSI}, and Δ_{Hb}, respectively with elbow moments were compared. This paper aims to find the suitable muscle oxygen indices to evaluate static and dynamic muscle contraction force.

2 Methods and Materials

2.1 Subjects and Instruments

Eight healthy male subjects(age 24.4±3.3 years, height 174.5±6.6 cm, and weight 71.8±10.5 kg) participated in the experiment after giving informed consent. The subjects were healthy and didn't do strenuous exercise in 24 hours before the tests.

Two instruments were used in the experiment. The instrument BTE Primus RS, which was developed by BTE of America, was used to collect elbow flexion moments. Force data was collected at 200Hz. The instrument PortaMon, which was developed by Artisnis of the Netherlands, was used to get muscle oxygenation and blood volume. PortaMon transferred data to a computer through Bluetooth technology with broadcast range of 30m. Data was collected at 10Hz.

2.2 Procedures

The subjects stood in front of BTE with their right elbow flexing 90° and hand grabbing the horizontal handle. PortaMon was attached to a subject by taping on biceps. The C_{oxy}, C_{deoxy}, $C_{Hb/Mb}$, and TSI of biceps, as well as the operation forces were recorded continuously.

Isometric elbow flexion exercise performed at four different force levels, 100%, 80%, 50%, 30% of the maximal voluntary contraction (MVC), with three minutes' rest in between. Each level repeated 3 times with one minute in between. Each elbow flexion lasted for 10s. As soon as subjects started to contract, a venous occlusion was applied in the upper arm. 80%, 50%, 30%MVC were calculated by the maximal value of repeated maximal voluntary contraction. The weight of the handle and subject's right arm was also considered, as it influenced the actual elbow moments. It could be excluded through measuring the moments when subjects were relaxed.

Isokinetic elbow exercise performed at the speed of 60°/s in the range of 30°~150°. Subjects made maximal force and repeated 5 times consecutively.

2.3 Data Processing and Statistics

In isometric elbow flexion exercise, V_{oxy}, V_{deoxy}, and V_{TSI} were determined by the linear change part of C_{oxy}, C_{deoxy}, and TSI immediately after occlusion. The slopes of the linear parts were taken as V_{oxy}, V_{deoxy}, and V_{TSI} of the muscle. Δ_{Hb} was determined by the difference of Hb/Mb between rest and exercise. The four indices were calculated from the muscle oxygen data collected in the same period. They were normalized to eliminate individual differences. For each subject and each index, the values were transformed to the percentages of the highest value of that index.

Correlation and variation of the indices were calculated. Pearson coefficients between normalized indices and different force levels, as well as the subjects' average values of coefficient of variation (*CV*) in each index were both calculated. *CV* indicates the within-subject variability derived from three repeated measurements of each force level. The equation is as follows:

$$CV\% = std.(A) \,/\, average(A) \tag{1}$$

where *A* represents the three repeated measurement values, *std.(A)* is the standard deviations of *A*, *average(A)* is the average value of *A*.

In isokinetic elbow exercise, the operation force and Δ_{Hb} during flexion movement were selected to make Pearson correlation analysis. The sampling frequency of operation force and muscle oxygen indices were different. In order to eliminate the difference of the data number between operation force and muscle oxygen indices, the uniform sampling method was used to handle operation force data.

3 Results

3.1 Muscle Oxygen Situation in Isometric Exercise

The maximal elbow flexion moments were 38.9±7.9Nm. Subjects performed obvious different maximal forces, distributing from 26.2Nm to 47.8Nm. However, each subject performed steady force in three repeated maximal elbow flexions. The average value of CVs was only 5.3.

Fig.1 showed the muscle oxygen situation of one subject during isometric elbow flexion exercise. It was similar with other subjects. Four indices were steady when subjects were relaxed. As soon as the biceps started to contract, all the indices except TSI obviously fell down. Then they performed different change. HbO_2/MbO_2 was consumed during muscle contraction. As long as the muscle contraction force was steady and the HbO_2/MbO_2 was enough, the decreasing rate of HbO_2/MbO_2 was almost linear. The changing rate fell down in a few seconds until the blood couldn't provide enough oxygen. At the same time, the consumed HbO_2/MbO_2 transferred to HHb/HMb, resulting in the increase of HHb/HMb and decrease of TSI. The changing rates of HHb/HMb and TSI were also linear in the first seconds and then fell down. Compared with HbO_2/MbO_2, HHb/HMb, and TSI, the content of Hb had little change in the period of steady muscle contraction.

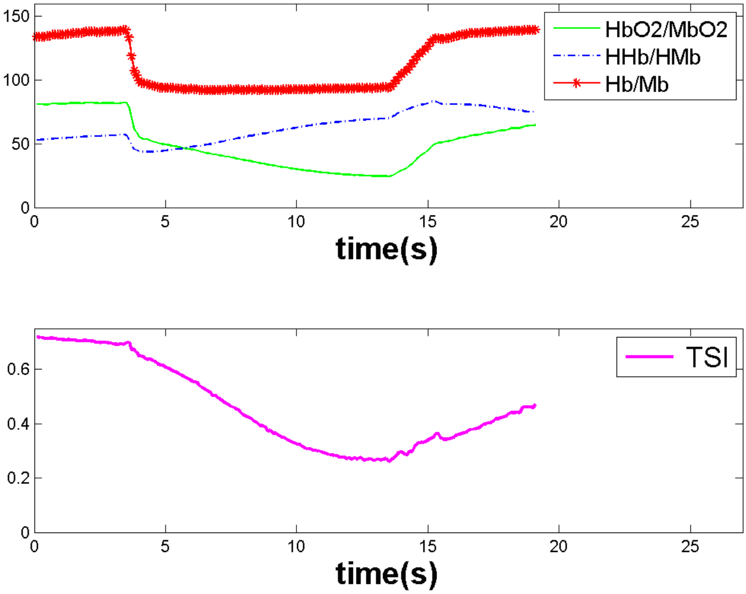

Fig. 1. Muscle oxygen content in response to isometric elbow flexion(100%MVC)

3.2 Muscle Oxygen Situation in Isokinetic Exercise

Fig.2 showed change process of the muscle oxygen of one subject during isokinetic elbow exercise. It was similar with other subjects. HbO_2/MbO_2, HHb/HMb, and TSI performed obvious differences between the five motion cycle. HbO_2/MbO_2 and TSI reduced gradually during isokinetic exercise. At the same time, HHb increased gradually. It was because that biceps didn't have enough rest during exercise, which resulted in untimely recovery of muscle oxygen. Hb/Mb performed obvious periodicity in the five motion cycle. It had more regular changes than the other three indices. Lack of muscle oxygen and rest had little influence on Hb/Mb.

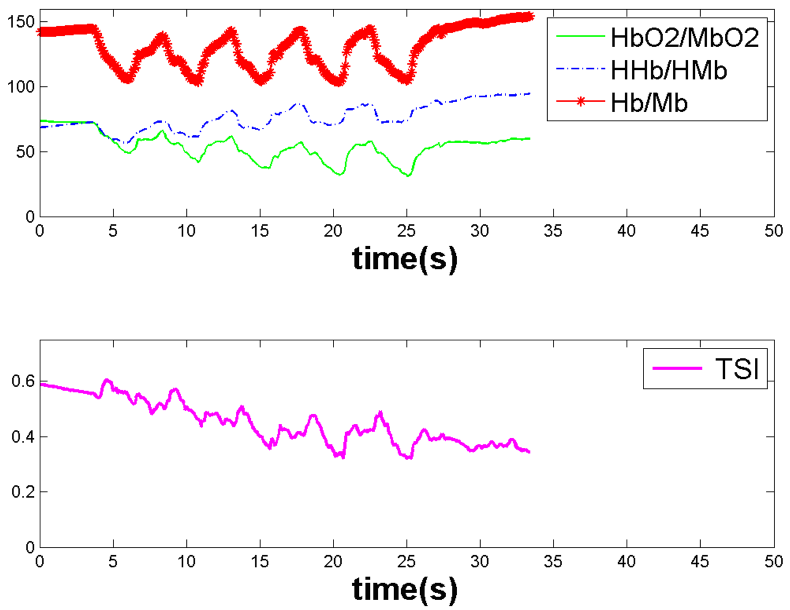

Fig. 2. Muscle oxygen content in response to elbow isokinetic exercise

4 Discussion

4.1 Correlations of Different Muscle Oxygen Indicators and Joint Torques in Isometric Elbow Exercise

All of the four indices were notably correlated with elbow flexion torques (Table 1). The coefficients of correlation ranged from 0.793 to 0.844. The CV ranged from 12.1 to 19.9. These results corresponded to previously reported findings. Praagman[5] found that V_{oxy} was notably correlated with elbow flexion torques. The correlation coefficient r =0.73, p <0.01. So both oxygenation and blood volume could be used in static musculoskeletal biomechanical mode validation. For this purpose, linear equations were made between indices and elbow flexion torques (Table 1). The equations could calculate the normalized elbow flexion torques and biceps contraction force through oxygenation and blood volume.

Table 1. Correlation and linear equation between muscle oxygen indices and external force

Index	Pearson		CV	a	b
	r	p			
V_{oxy}	.801	.000	13.4	0.920	0.011
V_{deoxy}	.793	.000	19.9	0.889	0.073
V_{TSI}	.843	.000	13.1	0.788	0.164
Δ_{Hb}	.844	.000	12.1	0.978	-0.021

Force=a**Index*+b.

Among the four indices, Δ_{Hb} demonstrated the highest correlation with external force, and the lowest variation. It corresponded to previously reported findings. Robert[4] found that Δ_{Hb} was more stable than V_{oxy} in repeated knee flexion exercise. As a result, Δ_{Hb} was more reliable to evaluate static muscle contraction force, and to validate musculoskeletal system biomechanical model.

4.2 Correlation of Δ_{Hb} and Joint Torque in Isokinetic Elbow Exercise

Workers often carry out tasks with dynamic posture and operation force. So it need to analyze the correlation of muscle oxygen and joint torques in dynamic movements. Fig.2 showed that continuous movement affected Coxy, Cdeoxy, and TSI, thereby affected Voxy, Vdeoxy, and VTSI. ΔHb was not influenced by these factors. So it was selected to evaluate the dynamic muscle contraction force.

Fig.3 showed Δ_{Hb} and elbow torques in isokinetic elbow exercise. The data came from the same subject with Fig.2. In one motion cycle, the elbow flexed first and then extended. Δ_{Hb} gradually turned larger in elbow flexion, and was largest at the end. When elbow started to extend, biceps stopped to contract and Δ_{Hb} gradually reduced. It was not completely corresponded with joint torques. The joint torques was largest at the middle of elbow flexion or extension.

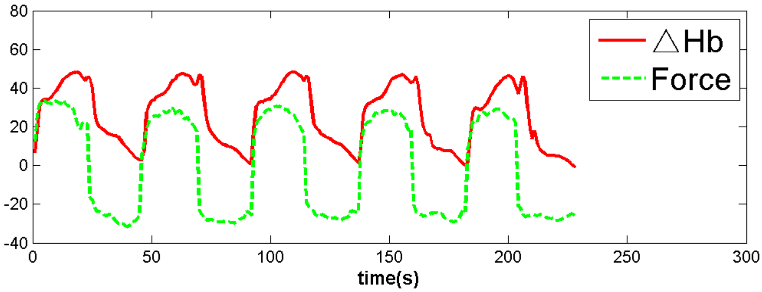

Fig. 3. Δ_{Hb} and elbow torques of one subject in isokinetic elbow exercise

Correlation of Δ_{Hb} and joint torques in isokinetic elbow exercise was analyzed. The normalized torques and Δ_{Hb} of 8 subjects during flexion movement were made Pearson correlation analysis. The correlation coefficient $r = 0.526$, $p<0.01$. Linear equation was as follows:

$$Force=0.434*\Delta_{Hb}+0.335 \quad (2)$$

The correlation coefficient of Δ_{Hb} in isokinetic exercise was smaller than that in isometric exercise. The linear equations of isokinetic exercise and isometric exercise were also different. It might be because the changing joint angles during exercise influenced the muscle length. Ruiter[7] reported that muscle oxygen was influenced by the muscle length and muscle fiber architecture. As a result, the correlation coefficient decreased. Although Δ_{Hb} was influenced by joint angles, it had a small correlation with joint moments, and could be used as a reference index to evaluate dynamic muscle contraction force.

5 Conclusions

In isometric exercise, oxygenation and blood volume in skeletal muscle could be used to evaluate muscle contraction force. Δ_{Hb}, which reflects the change of blood volume, was better than other three indices. As its' correlation efficient with joint moments was the highest, and variation was the lowest. In isokinetic exercise, blood volume demonstrated obvious periodicity in different motion cycles, and had low correlations with joint moments. Oxygenation indices performed obvious differences between the five motion cycles.

In conclusion, blood volume was found to be suitable to estimate the static and dynamic muscle contraction force, and validate musculoskeletal system biomechanical model.

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