Surface Electromyogram–Based Detection of Muscle Fatigue during Cyclic Dynamic Contraction under Blood Flow Restriction

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Abstract— **Surface electromyogram (SEMG) measurements employing a bipolar configuration are generally used to evaluate muscle fatigue. However, the changes in the SEMGs accompanying fatigue cannot be detected in some cases. We evaluated the differences in the detection of muscle fatigue during isometric and dynamic contraction between monopolar and bipolar configurations for measuring SEMGs. The results illustrated that the monopolar configuration is well suited for detecting waves slowed by muscle fatigue. In this study, the effectiveness of the monopolar configuration during dynamic contraction under blood flow restriction was verified. Our findings suggested that the monopolar configuration can detect changes in muscle fatigue with greater sensitivity than the bipolar configuration even under blood flow restriction.**

I. Introduction

Strength training is an important component of exercise programs for sport participation and general health maintenance. It serves to increase or suppress reductions in muscle quantity, which is important for independent living and preventing the need for long-term care [1]. However, as the load intensity of strength training [40–60% intensity of one repetition maximum (1RM)] is excessive for the elderly and patients with muscle atrophy, it is often difficult to perform this training appropriately. Therefore, low-intensity strength training with muscle blood flow restriction (Kaatsu training) has been developed [2]. This training method is effective even at low intensity (20% intensity of 1RM).

Strength training tends to result in increasing muscle fatigue due to exercise repetition. Muscle fatigue can result in muscle stiffness, muscle tension, and the development of sinewy muscles. To prevent these issues, an objective method of assessing muscle fatigue is required, which can be accomplished using any of the following techniques: 1) biochemical methods such as blood lactate measurements; 2) mechanomyography; and 3) electromyography. Surface electromyography has been widely used because it is noninvasive and represents a relatively simple measurement. Observation of wave slowing is generally used to assess muscle fatigue using surface electromyography, and this method has been validated in several studies [3]-[5].

However, it has been reported that under some exercise conditions, the change in the surface electromyogram (SEMG) accompanying muscle fatigue may be undetectable with a bipolar configuration (BPC), which is generally used for measuring SEMGs [6]-[8]. One solution is to record the electromyogram (EMG) using the monopolar configuration (MPC) instead of the BPC. Because the MPC has a wide detection region and flat frequency characteristic relative to the BPC, it can potentially facilitate the detection of changes in SEMGs due to fatigue. To confirm this hypothesis, we evaluated the differences in the detection of muscle fatigue using both configurations under static and cyclic dynamic contractions. Our findings suggest that the MPC is well suited for the detection of wave slowing caused by muscle fatigue [9]-[11].

The purpose of this study was to examine whether the MPC is effective for detecting muscle fatigue during cyclic dynamic muscle contraction under blood flow-restricted (BFR) conditions, which simulates Kaatsu training. The target exercise and muscle were the seated dumbbell arm curl and biceps brachii muscle, respectively. As a reproducibility index of Kaatsu training, muscle oxygen dynamics was measured using near-infrared spectroscopy. As an index of muscle fatigue, the slope of the time series regression line of the mean power frequency (MPF) was adopted. In addition, the threshold for muscle fatigue was defined on the basis of the slope [12], [13].

II. Experimental Methods

A. Movement conditions

The subjects in this study were five healthy 20-year-old adult males, three of whom were right-handed. Each subject was informed in advance of the content and risks of the experiment, and all participants provided written consent for voluntary participation.

The subjects performed seated dumbbell bicep curls three times using the dominant arm according to the concrete enforcement procedure depicted in Figure 1. A metronome was used for regulating each working speed. Before the exercise, blood flow in the arm was restricted by exerting a pressure of 200 mmHg on the upper arm using a pneumatic cuff (aneroid sphygmomanometer, Q9917, YAMASU).

First, each subject was seated with a 3-kg dumbbell in his dominant hand, with the elbow resting on the desk but with the

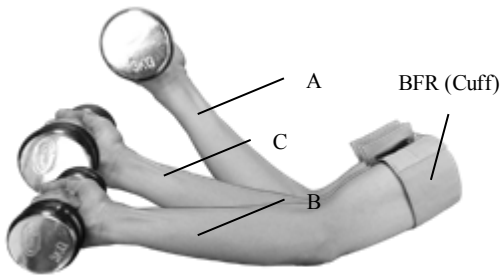

Figure 1. Enforcement procedure for seated dumbbell bicep curls (A: upward, B: downward, C: rest).

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dumbbell not touching the desk surface. Next, the subject bent his elbow, bringing the dumbbell toward his shoulder over a period of 2 s, after which he straightened the elbow and lowered the dumbbell to the starting position over a period of 2 s in a slow and controlled manner (Figs. 1 A and B). After four upward-and-downward movements, the elbow was held at rest for 4 s at a 45° angle (Fig. 1 C, resting state). These steps were continuously performed for a series of 15 repetitions.

It was assumed that the target muscle became increasingly fatigued with increasing repetitions of seated dumbbell bicep curls. Therefore, considering the effect of fatigue on the measured value, the experiment was performed once per day by each subject, and each trial was assumed to be independent.

B. Measurement conditions

Muscle oxygen metabolism was measured using an infrared oxygen-monitoring device (NIRO-200NX, Hamamatsu Photonics K.K.). Irradiation and detection probes were placed perpendicular to the muscle fibers over the mid-portion of the muscle belly (Fig. 2). The distance between the probes was set at 40 mm, and the sampling frequency was set at 20 Hz. We measured the oxygenated hemoglobin (O2Hb, μmol*cm) and deoxygenated hemoglobin (HHb, μmol*cm) concentrations.

We simultaneously measured the SEMG signal of the biceps brachii muscle using both the MPC and BPC. Active electrodes (material: gold; shape: disc; diameter: 14 mm; AP-C300, DIGITEX LAB) were used as recording, ground, and reference electrodes. The SEMG signals recorded by the electrodes were sampled at 1000 Hz using a built-in A/D converter in a biological signal recording apparatus (PolymateII AP216, DIGITEX LAB). To prevent noise from getting mixed with the SEMG signal, we conducted the SEMG measurements in a shielded room. In addition, the signal after A/D conversion was filtered using a high-pass filter with a cutoff frequency of 5 Hz and a notch filter.

In the MPC, the recording electrodes were placed both over the mid-portion of the biceps brachii muscle and at the elbow, which displays an electrical value of near 0, as shown in Figure 2. In the BPC, the recording electrodes were placed over the same muscle parallel to the longitudinal axis of the muscle fiber and fixed in a manner that did not sandwich the neuromuscular junction. The electrodes in the BPC had a center-to-center spacing of 20 mm. In both configurations, the ground and reference electrodes were placed over the elbow and wrist, respectively.

III. Data Analysis

For each measurement, data analysis was performed over a 1200-ms period during the second half of the 4000-ms rest period (Fig. 3 C').

A. Muscle oxygen metabolism

As a reproducibility index of Kaatsu training, O2Hb, HHb, and the total hemoglobin concentration (cHb, μmol*cm) obtained from the sum of the O2Hb and HHb values were used. The procedure was conducted as follows.

1) The amount of variation of each hemoglobin concentration was computed using the following three equations:

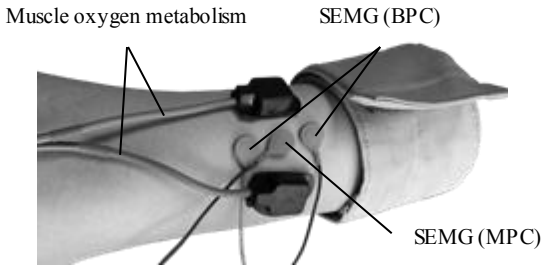


Figure 2. Probe and electrode positions of each measurement system.

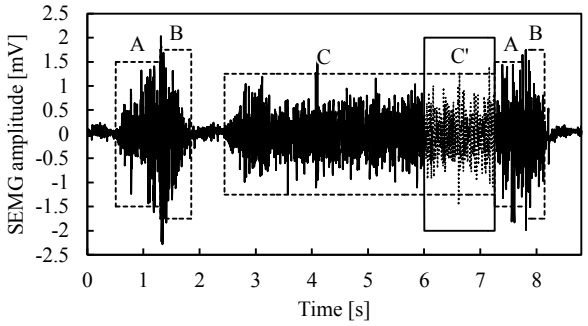


Figure 3. Electromyogram measured during seated dumbbell bicep curls and the classification of movement (A: upward, B: downward, C: rest, C′ : analysis section).

$$\Delta O2Hb(T) = O2Hb(T) - O2Hb(1) \quad (1)$$

$$\Delta HHb(T) = HHb(T) - HHb(1) \quad (2)$$

$$\Delta cHb(T) = \Delta O2Hb(T) + \Delta HHb(T) \quad (3)$$

where $O2Hb(i)$ and $HHb(i)$ denote the average value of each hemoglobin concentration in the i set.

2) The average value and standard error of the variation of each hemoglobin concentration were computed for all subjects.

3) A two-sided, one-sample t-test with a significance level of 0.05 was employed. The targets for the comparison of significance were the variation in the hemoglobin concentration in simultaneous data sets between the BFR and unrestricted (CON) conditions. The data of the CON condition were measured using the same procedure described for the BFR condition.

B. Surface electromyography

In this study, we adopted the regression line slope of the MPF time series of the SEMG measured using both configurations as an indicator of muscle fatigue. The threshold for muscle fatigue was defined according to previous research [12], [13].

The power spectral density $W(f)$ was estimated from each set using a Hanning window and Fast Fourier Transform, and the MPF was computed according to the following formula:

$$MPF = \frac{\sum_{f=f_l}^{f_h} f \cdot W(f)}{\sum_{f=f_l}^{f_h} W(f)} \quad (4)$$

where f_l and f_h denote the minimum and maximum frequencies that define a frequency range for the calculation of

MPF, respectively. The values were set at f_l = 5 Hz and f_h = 300 Hz. The MPF values were normalized against the starting value, which was assumed to be 100%.

The regression line of the normalized MPF values for the 15 sets was determined, and its slope a and intercept b were registered. The normalized mean squared error (NMSE) was defined as the mean squared error (MSE) divided by the intercept b as follows:

$$N_{MSE} = \frac{MSE}{b} \tag{5}$$

When the conditions of the next formula were fulfilled, it was judged that muscle fatigue had occurred.

$$\left(a \leq a_j\right) \text{ AND } (N_{MSE} \leq 0.1) \tag{6}$$

a_j is the threshold value of the slope of the regression line, and the value was gradually increased in the manner of $a_j = -0.5, -0.6, \ldots, -1.0$ in this research.

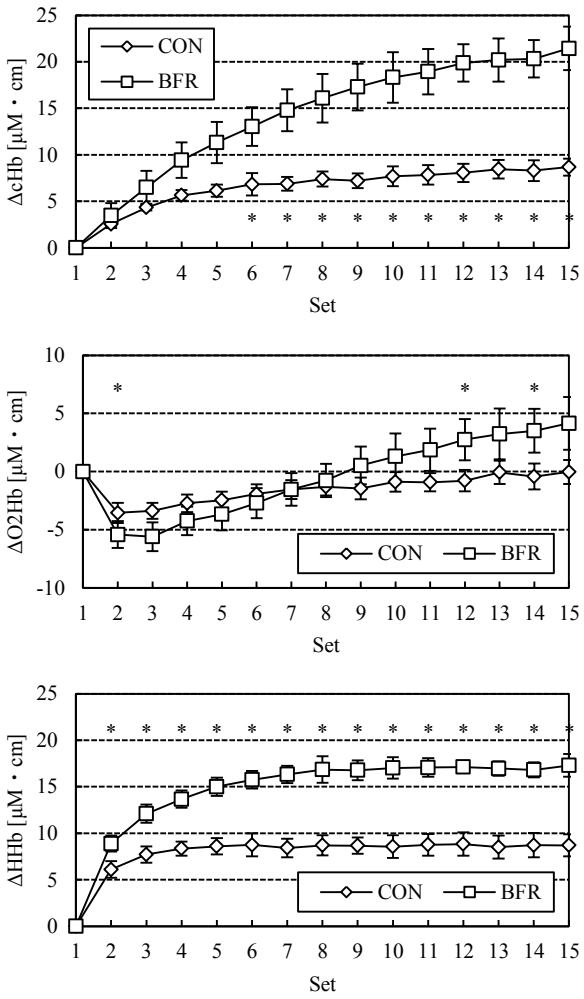
IV. Results and Discussion

A. Muscle oxygen metabolism

Before the explanation of these results, we will explain the mechanism by which Kaatsu training increases or suppresses reductions in muscle quantity even at a low load intensity. First, blood vessels in the muscle are pressed via external compression of the upper arm base, thus inhibiting blood circulation. Consequently, the flow of oxygen-rich arterial blood is inhibited, and the slow-twitch fibers, which need oxygen, cannot function. As a result, the relative load intensity increases, and easily fatigued fast-twitch muscle fibers, which do not require much oxygen, are recruited. In other words, even with low-intensity loads, the muscle fibers are subjected to conditions that simulate high-intensity exercise [14].

Figure 4 depicts the average value and standard error of the variation of each hemoglobin concentration (ΔO2Hb, ΔHHb, and ΔcHb). The result under the CON condition is also presented for comparison. As shown in Figure 4(A), ΔcHb under the BFR condition monotonically increased throughout the experiment. By contrast, ΔcHb under the CON condition gradually increased up to the 6th set and remained nearly constant for the remainder of the sets. Comparing the conditions, ΔcHb under the BFR condition was larger than that under the CON beginning at the 3rd set, and the difference became significant at the 6th set ($P < 0.05$). This finding indicates retention of intra-muscular blood caused by the increase in peripheral vascular resistance due to external compression suggesting that the muscle displayed intravenous congestion.

As shown in Figure 4(B), ΔO2Hb under both conditions decreased until the 3rd set and then gradually increased throughout the remainder of the experiment. However, the degree of change tended to be larger under the BFR condition, with significant differences observed for the 2nd, 12th, and 14th sets ($P < 0.05$). As shown in Figure 4(C), ΔHHb under both conditions increased rapidly during the early sets and remained constant over the remaining sets. Additionally, ΔHHb under the BFR condition was significantly larger than that under the CON condition beginning at the 2nd set ($P < 0.05$).



From top to bottom: (A) ΔcHb, (B) ΔO2Hb, (C) ΔHHb

Figure 4. Variation of oxygenated hemoglobin (ΔO2Hb), deoxygenated hemoglobin (ΔHHb), and total hemoglobin (ΔcHb) and under blood flow-restricted (BFR) and control (CON) conditions. Values are presented as the mean ± standard error of 15 samples. The symbol * denotes a significant difference at the 5% significance level.

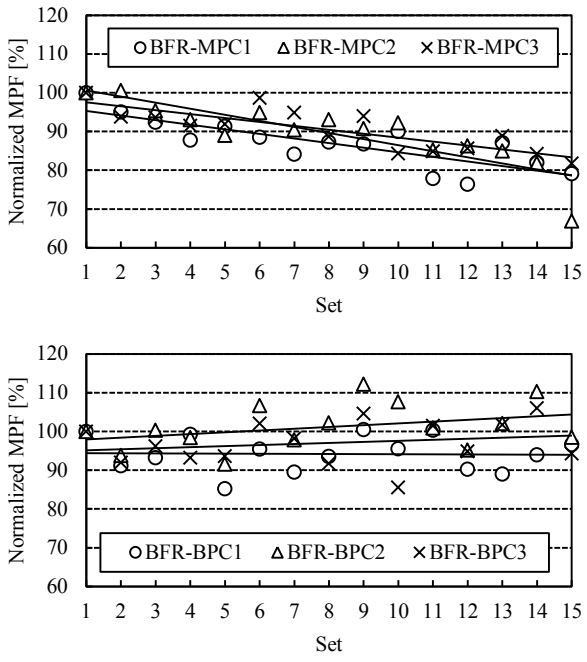
During the early stages, the changes in the variables tended to be similar between the two conditions, although the increase of ΔHHb differed between them. These early stages under the BFR condition can be considered the time during which slow-twitch fibers are primarily functioning, similar to the CON condition, because the inhibition of blood circulation is not sufficient. In the middle or later stages, the findings under the BFR condition differed from those under the CON condition. First, ΔO2Hb was larger under the BFR condition than under the CON condition. It is believed that O2Hb accumulated because it became less likely to be consumed. In addition, although ΔHHb remained nearly constant from the middle stage under both conditions, it is believed that oxygen consumption was lower under the BFR condition as venous blood flow was inhibited under this condition. Although the BFR condition of the present study differed in some aspects from the theory of Kaatsu training, it can be assumed that the intramuscular environment was hypoxic and that muscle fibers were subjected to a high intensity-like environment. The hypoxic condition and intravenous congestion resulted in the accumulation of anoxic metabolic products such as lactic acid,

hydrogen ions, and adenosine, which inhibit the energy production needed for muscle activity and result in a loss of muscle strength. To compensate for this loss in muscle strength, it is inferred that more motor units, including both slow- and fast-twitch types, are recruited.

B. SEMG

Figure 5 shows the typical time series variation of the MPF measured using both configurations. As shown in Figure 5(A), using the MPC, the regression line of the MPF values tended to decrease clearly in all trials. a and NMSE of the regression line met the threshold values in all of the trials, indicating that muscle fatigue was experienced in all of the trials. The wave slowing induced by muscle fatigue was successfully measured using the MPC. However, in the BPC, the regression line of the MPF values was virtually unchanged or increased despite the simultaneous measurements [Figure 5(B)]. The threshold for muscle fatigue was not reached in any of the trials, even at $a_j = -0.5$.

Figure 6 shows the results of the judgment of muscle fatigue by the subjects. At $a_j = -0.5$, 10 trials reached the threshold for muscle fatigue under the MPC, versus eight under the BPC. Although the difference in the number of judgments was small at $a_j = -0.5$, it increased gradually as a_j increased, and the superiority of the MPC became evident. These results indicate that the MPC is well suited for detecting waves slowed by muscle fatigue even under muscle blood flow restriction [9], [11].



From top to bottom: (A) Monopolar configuration, (B) Bipolar configuration

Figure 5. Normalized mean power frequency in one of the subjects. The different symbols denote trials 1, 2, and 3.

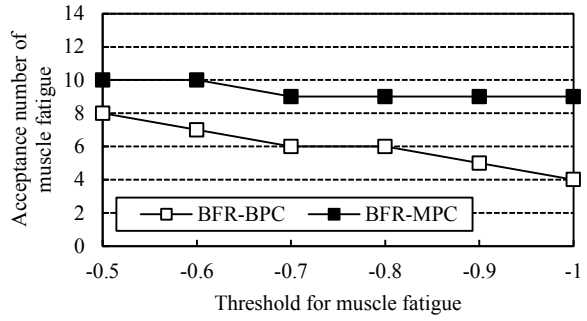


Figure 6. Assessment of muscle fatigue

One disadvantage of the MPC is that power line interference may be higher than that for the BPC. To determine the effect of the noise, the MPF values were compared in the presence or absence of a notch filter. The difference was extremely small (less than 2 Hz). In this research, the noise did not significantly influence the result.

V. Conclusion

Our findings suggest that the MPC can detect changes in muscle fatigue with greater accuracy than the BPC even under blood flow restriction. In the future, we plan to develop a real-time muscle fatigue assessment system that will leverage the advantages identified in this study.

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