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Detection of EMG-based muscle fatigue during cyclic dynamic contraction using a monopolar configuration

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Abstract— **Measurement of surface EMG signals is usually performed using the bipolar (single differential) configuration. However, even if contraction during exercise is performed until near-complete exhaustion, the change in the surface EMG accompanying the fatigue could be undetectable using the bipolar configuration. In order to overcome this disadvantage, this study proposes the measurement of surface EMG using the monopolar configuration. Experimental results show that the monopolar configuration can detect the change in muscle fatigue with greater sensitivity and better stability, as compared to the bipolar configuration.**

I. Introduction

Excessive muscle movement and training may cause damage or fatigue, resulting in muscle performance degradation. It has been reported that accumulation of muscle fatigue generates muscle stiffness, muscle tension, and progression to sinewy muscle. An objective evaluation method for muscle fatigue is needed, and could be accomplished using one of several techniques: 1) biochemical methods such as blood lactate concentration; 2) mechanomyogram (MMG); and 3) electromyography (EMG). Surface EMG has been widely used because it is noninvasive and represents a relatively easy measurement. The observation of wave slowing is generally used to assess muscle fatigue using surface EMG and the method has been validated in many papers [1]-[3].

However, it has also been reported that even if contraction during low-intensity static exercise is performed until near complete exhaustion, the change in the SEMG accompanying the fatigue may be undetectable by bipolar configuration [4]-[6]. In order to resolve these problems, we evaluated the differences in the detection of muscle fatigue using the monopolar configuration for measuring surface EMG instead of the bipolar configuration that is generally used [7]-[9]. Our findings suggest that the monopolar configuration is well suited for the detection of wave slowing caused by muscle fatigue [7]-[9].

This study measured the surface EMG signal by means of monopolar and bipolar configurations during seated dumbbell bicep curls and compared and evaluated their differences in the detection of muscle fatigue. EMG measurement using the monopolar configuration was validated for both static and dynamic muscle contraction movements.

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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 gave written consent for voluntary participation. The subjects performed seated dumbbell bicep curls three times according to the concrete enforcement procedure depicted in Figure 1.

First, each subject was seated with a 3 kg dumbbell in his dominant hand, with the elbow resting on the desk but with the dumbbell not touching the desk surface. Next, he bent his elbow bringing the dumbbell toward his shoulder for 2 s, and then straightened the elbow and lowered the dumbbell back to the start position for 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 20 repetitions (reps).

It was assumed that with increasing number of seated dumbbell bicep curls, the target muscle became more fatigued. 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.

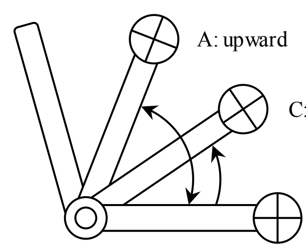


Figure 1. Enforcement procedure for seated dumbbell bicep curls.

B. Measurement conditions

We simultaneously measured the surface EMG signal of the biceps brachii muscle using both the monopolar and the bipolar configurations. Active electrodes (material: gold; shape: disc; diameter: 14 mm; AP-C300, DIGITEX LAB) were used as recording, ground, and reference electrodes. The surface EMG 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 being mixed into the surface EMG signal, we conducted the surface EMG measurements in a shielded room.

In the monopolar configuration, the recording electrodes were placed both over the mid-portion of the biceps brachii muscle and at the elbow, which represents an electrical value of near 0, as shown in Figure 2. In the bipolar configuration, the recording electrodes were placed over the same muscle parallel to the longitudinal axis of the muscle fiber and were fixed so as to not sandwich the neuromuscular junction. The electrodes in the bipolar configuration 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.

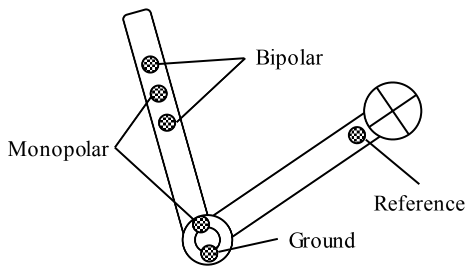


Figure 2. Electrode positions in both configurations.

III. DATA ANALYSIS

In this study, we observed changes in the mean power frequency (MPF) of the surface EMG over a time series as an indicator of muscle fatigue. The threshold for muscle fatigue was defined according to previous research [10]-[12].

A. Computation of MPF

We extracted 20 surface EMG measurements at the resting state from the entire surface EMG measurement (Fig. 3 C). The power spectral density (PSD) $W(f)$ was estimated from each measurement using a Hanning window and fast Fourier transform (FFT), and MPF was computed according to the following formula:

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

where f_l and f_h denote the minimum and maximum frequencies that define a frequency range for the calculation of MPF. The values were set as $f_h = 300$ Hz and $f_l = 5$ Hz. The MPF values were normalized against the starting value, which was assumed to be 100%.

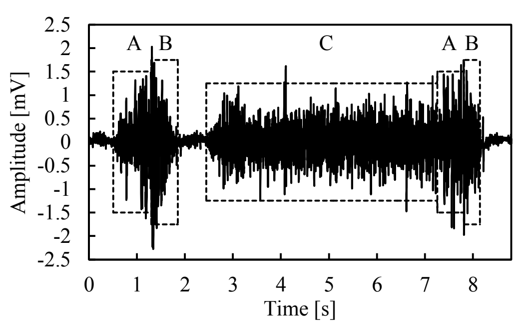


Figure 3. EMG during seated dumbbell bicep curls and classification of movement. *(A: upward, B: downward, C: rest)*

B. Detection of muscle fatigue

The regression line of the normalized MPF values for the 20 measurements was determined, and its slope a and intercept b were registered. Normalized mean squared error (N_{MSE}) was defined as the mean squared error (MSE) divided by the intercept b as follows:

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

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

$$(a \leq -0.1) \text{ AND } (N_{MSE} \leq 0.1)$$

Signal-to-variance ratio (S/V), which can evaluate the stability of change, was also defined using the following equation:

$$S/V = \frac{a}{\sqrt{MSE}}$$

IV. RESULTS AND DISCUSSION

Figure 4 shows the typical time series variation of the MPF measured using both configurations. As shown in Figure 4, in the monopolar configuration, the regression line of the MPF values tended to decrease clearly in all trials. The monopolar configuration successfully measured the wave slowing induced by muscle fatigue. However, in the bipolar configuration, there was a case where the regression line of the MPF values was virtually unchanged or increased despite the simultaneous measurements.

Table 1 summarizes the regression line slope (a), normalized mean squared error (N_{MSE}), S/V, and judgment of muscle fatigue. First, the judgment of muscle fatigue is discussed. In the monopolar configuration, the slope (a) and the normalized mean squared error (N_{MSE}) of the regression line met the threshold value in all the trials for all subjects (15 trials in total). This means that all of the trials were observed to experience muscle fatigue. Conversely, in the bipolar configuration, six trials did not reach the threshold for muscle fatigue. From these results, it is concluded that the monopolar configuration can detect the onset of muscle fatigue better than the bipolar configuration can. In this judgment, since MPF is normalized as 100%, we set the threshold values at a fixed value of 0.1 based on previous research [10]-[12]. With respect to concrete application, the value of the threshold is a point for further examination.

With respect to S/V, the larger the absolute value of S/V, the smaller was the variation in MPF and the larger was the change in MPF. This indicates that the stability of the decreasing tendency of MPF can be examined by comparing S/V for both configurations. Based on this comparison, the absolute value of S/V in the monopolar configuration was larger than that of the bipolar configuration in 10 trials. This therefore suggests that the tendency toward decreasing MPF in the monopolar configuration would change in a more stable manner than that in the bipolar configuration.

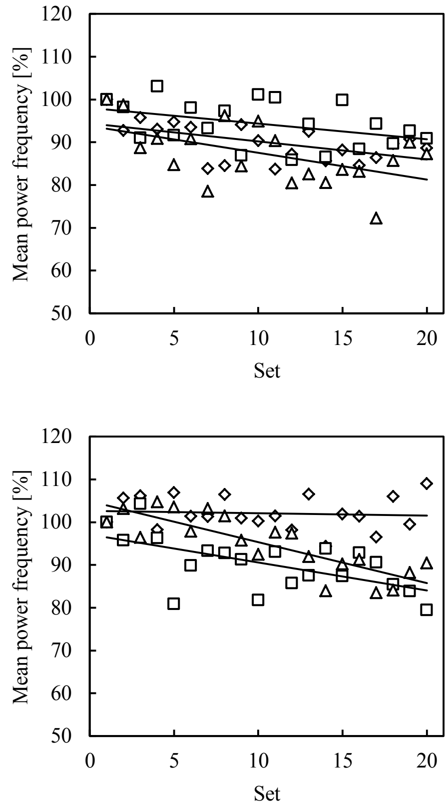
Finally, through consideration of these results, it can be concluded that the monopolar configuration detects muscle fatigue more accurately and with greater stability than the bipolar configuration does. Because the monopolar configuration has a wider derivation range and smaller frequency characteristic than the bipolar configuration, it can detect changes in surface EMG due to muscle fatigue with greater sensitivity [7]-[9], [13]. One disadvantage of the monopolar configuration is that power line interference may be higher than that for the bipolar configuration. A relatively larger power line interference was actually observed in the measurement data obtained using the monopolar configuration. In order to determine the effect of the noise, the MPF values were compared in the presence or absence of a notch filter. The difference was very small, below 2 Hz (Fig. 5). In this research, the noise did not significantly influence the result. The monopolar configuration seems worthwhile as a method for the detection of muscle fatigue, although there is a need to further investigate the influence of noise.

V. CONCLUSION

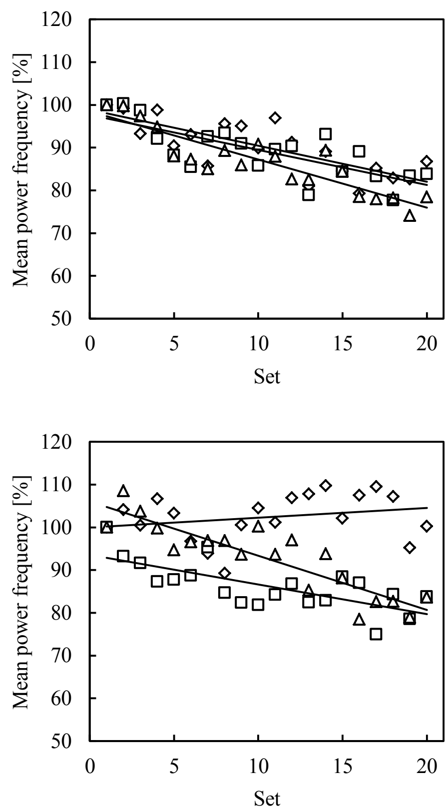
This study verified the effectiveness of the monopolar configuration for detecting muscle fatigue. Our findings suggest that the monopolar configuration can detect the tendency of muscle fatigue with greater accuracy and stability than the bipolar configuration can. In the future, we plan to develop a real-time muscle fatigue assessment system that will leverage the advantages identified here. A subsequent study will examine the influence of power line interference in the general environment, because in this study, surface EMG was measured in a shielded room.

TABLE I. REGRESSION LINE SLOPE (a), NORMALIZED MEAN SQUARED ERROR (N_{MSE}), SIGNAL-TO-VARIANCE RATIO (S/V), AND ASSESSMENT OF MUSCLE FATIGUE

Configuration		**Monopolar**			**Bipolar**		
		Tri 1	***Tri 2***	***Tri 3***	***Tri 1***	***Tri 2***	***Tri 3***
a	***Sub A***	-1.00	-0.31	-0.13	-1.03	-0.94	0.39
	Sub B	-0.42	-0.37	-0.62	-0.05	-0.65	-0.96
	Sub C	-0.64	-0.56	-1.14	-0.15	-1.39	-0.87
	Sub D	-0.84	-0.82	-1.13	0.23	-0.69	-1.27
	Sub E	-0.94	-0.54	-1.06	-0.44	-0.50	-0.54
N_{MSE}	***Sub A***	0.09	0.07	0.07	0.11	0.12	0.12
	Sub B	0.05	0.05	0.07	0.04	0.07	0.07
	Sub C	0.06	0.07	0.09	0.03	0.13	0.09
	Sub D	0.06	0.07	0.08	0.06	0.06	0.08
	Sub E	0.08	0.05	0.07	0.06	0.07	0.06
S/V	***Sub A***	-0.35	-0.12	-0.05	-0.33	-0.26	0.13
	Sub B	-0.20	-0.16	-0.24	-0.03	-0.26	-0.37
	Sub C	-0.26	-0.22	-0.39	-0.08	-0.42	-0.31
	Sub D	-0.33	-0.32	-0.41	0.10	-0.29	-0.44
	Sub E	-0.34	-0.24	-0.40	-0.19	-0.20	-0.22
muscle fatigue	***Sub A***	T	T	T	F	F	F
	Sub B	T	T	T	F	T	T
	Sub C	T	T	T	T	F	T
	Sub D	T	T	T	F	T	T
	Sub E	T	T	T	T	T	T

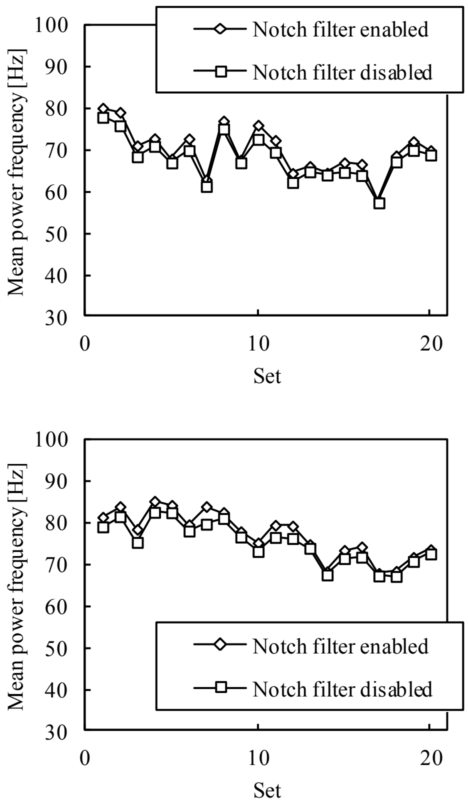


(a) Subject B

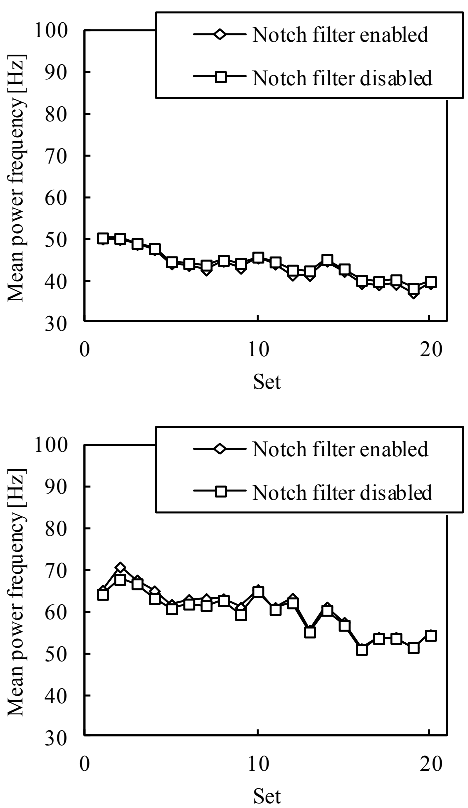


(b) Subject D

Figure 4. Normalized MPF. Each marker indicates trials 1, 2 and 3. *(up: monopolar, down: bipolar;)*



(a) Subject B



(b) Subject D

Figure 5. MPF. *(up: monopolar, down: bipolar)*

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