# Verification of the Muscle Fatigue Detection Capability of a Unipolar-Leads System Using a Surface Electromyogram Model

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***Abstract*— In this study, the muscle fatigue detection capability of bipolar and unipolar lead systems used for surface electromyogram measurement was verified by simulation. The constructed model simplified the isometric contraction of the biceps brachii. There were two simulation experiments: 1) the addition and deletion of white noise and 2) the addition and deletion of hum noise. The pattern result of simulation 1) suggested the possibility that the muscle fatigue detection capability of a unipolar-leads system was high. The pattern 2) result showed the unipolar-leads system had a small influence of filtering, and suggested that the mixing of hum noise could be disregarded.**

## I. Introduction

In a previous study, we detected the surface electromyogram (sEMG) of the bicep's brachii under isometric contraction by bipolar and unipolar lead systems, and verified the muscle fatigue detection capability. The frequency detected by the sEMG using the unipolar-leads system fell greatly, suggesting the possibility that muscle fatigue could be detected [1], [2]. However, because exerted muscular power was not always constant, measured values varied. The difference may have appeared in the muscle fatigue detection capability of bipolar and unipolar lead systems. Although variation was reduced by repeating the trial two or more times on the same subject, muscular power exerted may have declined due to the practice of movement. Moreover, because hum noise was mixed in the detected sEMG signal, the band elimination filter removed 47~53 Hz. However, compared with the unipolar-leads system, the frequency band of the bipolar-leads system is narrow, and the peak of the main frequency component exists near 50~60 Hz. When this was taken into consideration, the muscle fatigue detection capability of the unipolar leads system decreased, and the muscle fatigue detection capability of the bipolar leads system may have declined by filtering.

Owing to the mentioned experimental variation, a model that generates sEMG of the biceps brachii under isometric contraction was built, and the muscle fatigue detection capability of bipolar and unipolar lead systems was reanalyzed.

## II. Basic Structure of the Model

The model built for this study simplifies the isometric contraction of biceps brachii. The basic structure of the model consists of three parts: 1) generation of the distribution coordinates of a motor unit (MU) and a muscle fiber group, 2) a setup of physiological and anatomical parameters, and 3) generation of sEMG.

### A. Generation of the distribution coordinates of a MU and a muscle fiber group

In this model, the form of biceps brachii was denoted by an ellipse, and MUs and a muscle fiber groups were distributed throughout the inside of the ellipse (Fig. 1). The form of single MU in a cross-sectional view was made into a circle, and form of the single muscle fiber was made into a point. The forms of a single MU and a single muscle fiber in a side view were both represented by cylinders (Fig. 2). The coordinate system set the cylindrical shaft orientation along the z-axis, and set up the x-axis and y-axis radially.

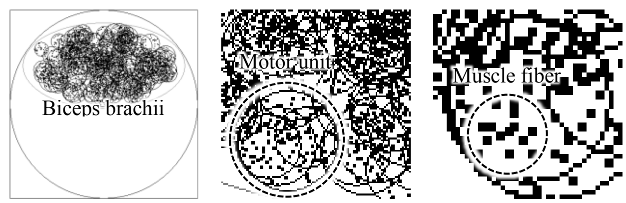


Figure 1. Structure of biceps brachii shown in the cross-sectional diagram

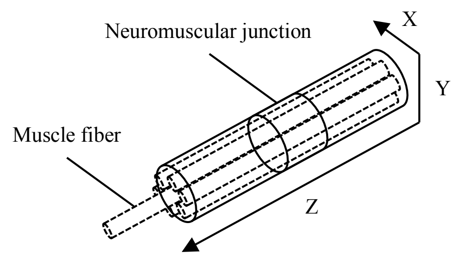


Figure 2. Structure of motor unit shown in the side diagram

### B. Setup of the physiological and anatomical parameters

Because there are many physiological and anatomical parameters, the main parameters in are listed in Table 1 [3]-[5]. Additional parameters are described in the literature [3]-[8].

### C. Generation of sEMG

The calculation method for the intracellular potential of a single fiber action potential (SFAP) and the potential detected by a body surface electrode is described [3]. The intracellular action potential, $e(z)$, was determined using the following formula:

$$e(z) = 763z^3e^{-2z} - 90 \quad (1)$$

where $z$ expresses the coordinates of a single muscle fiber. The potential detected with the coordinates $V_E$ of a body surface electrode $[z_0, y_0]$ is expressed by the following formula:

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$$V_E(z, z_0, y_0) = K'K''\left[\frac{\partial e(z)}{z} \cdot \frac{1}{r}\Big|_{s1} + \int_{+\infty}^{-\infty} \frac{\partial^2 e(z)}{\partial z^2} \cdot \frac{1}{r} dz - \frac{\partial e(z)}{\partial z} \cdot \frac{1}{r}\Big|_{s2}\right] \quad (2)$$

where $s1$ and $s2$ express the section at each end of a single muscle fiber. In the equation below, $r$ expresses the distance between the coordinates of the body surface electrode and the main coordinates of a single muscle fiber, in consideration of anisotropy.

$$r = \sqrt{(z_0 - z)^2 + \frac{\sigma z}{\sigma y} {y_0}^2} \quad (3)$$

The variables $\sigma z$ and $\sigma y$ express the conductivity of the cylindrical shaft orientation (z-axis) and a radial direction (y-axis), respectively. The factors $K'$ and $K''$ are given by formulas (4) and (5).

$$K' = \frac{A}{4\pi\sigma y} \quad (4)$$

$$K'' = \frac{\pi d^2 \sigma i}{4} \quad (5)$$

The variable $A$ is a scale factor, $\sigma i$ is intracellular conductivity, and $d$ is the diameter of a single muscle fiber. In this model, the sEMG is generated by temporospatially superimposing two or more SFAP(s).

## III. Simulation Conditions

### A. *Setup of the physiological and anatomical parameters*

In performing a simulation by this model, some of physiological and anatomical parameters were fixed. The fixed parameters were the total number of MUs (150), the number of the muscle fiber groups belonging to single MU (30), and the distribution coordinates of MU and the muscle fiber groups belonging to it. By fixing these parameters, the model was considered to be simulating a single subject. Variable parameters were the firing rate of MUs, the synchronization ratio of MUs, the muscle fiber conduction velocity, and an expansion and contraction ratio of a SFAP [3]-[6]. By changing these parameters, the model was considered to be simulating muscle fatigue under isometric contraction (Table 2). The sEMG signal was reproduced by detecting sEMG generated using the conditions above by bipolar and unipolar lead systems. Each simulation was executed 15 times.

### B. *The addition and removal of a noise signal*

In this study, in order to reproduce a survey of sEMG signals, addition and removal of white noise and hum noise were carried out. However, because the power-spectrum density of white noise was constant across all the frequency bands, white noise was not removed. In addition, because white noise displayed the normal random number characteristic, the observed white noise was strictly white Gaussian noise. Based on the actual measurement, hum noise made 50 Hz the object frequency band. Both noises were provided to the generated sEMG based on the signal to noise ratio (SNR) which was arbitrary and set. The following five patterns simulated addition and removal of both noises: (a) Normal sEMG, (b) Add 30 dB hum noise, (c) 30 dB hum noise removal, (d) Add 10 dB hum noise, (e) 10 dB hum noise removal. In addition, all patterns had white noise given by $SNR = 20$ dB.

## IV. Analysis Method

Analysis of sEMG generated under the simulation conditions in section III was conducted as follows.

1) After applying a humming window to the generated sEMG, Fast Fourier Transform was performed.

TABLE 1. Physiological and Anatomical Parameters

| | Name | Value | | |
|---|---|---|---|---|
| (a) | Total number of motor units | | 150 | pieces |
| (b) | Number of muscle fiber groups belonging to a single motor unit | | 30 | pieces |
| (c) | Diameter of biceps brachii | | 44 | [mm] |
| (d) | Diameter of single motor unit | Mean:<br>S. D.:<br>Range: | 6.5<br>0<br>±3~10 | [mm] |
| (e) | Diameter of single muscle fiber | Mean:<br>S. D.:<br>Range: | 55<br>1<br>±2 | [μm] |
| (f) | Coordinate distribution of single motor unit | Range: | ±{(c)-(d)} | [mm] |
| (g) | Coordinate distribution of single muscle fiber | Range: | ±(d) | [mm] |
| (h) | Total length of single muscle fiber | | 100 | [mm] |
| (i) | Coordinates of surface electrode | Distance:<br>Z axis:<br>Y axis: | 10<br>60<br>4 | [mm] |
| (j) | Conductivity | Intracellular:<br>Z axis:<br>Y axis: | 1.01<br>0.063<br>0.328 | [S/m] |

TABLE 2. Fatigue Stage of Each Parameter

| Parameter name | | Fatigue stage | | | | |
|---|---|---|---|---|---|---|
| | | *0* | *1* | ~ | *19* | *20* |
| Firing rate of motor units | [m/s] | 90 | 91.5 | ~ | 118.5 | 120 |
| Synchronization ratio of motor units | [%] | 0 | 5 | ~ | 95 | 100 |
| Muscle fiber conduction velocity | [m/s] | 3.7 | 3.675 | ~ | 3.225 | 3.2 |

| | | | | |
|---|---|---|---|---|
| Expansion and contraction ratio of single fiber action potential | [%] | 100 | 98.75 ~ 76.25 | 75 |

2) Mean power frequency (MPF) was computed by the following formula:

$$\frac{\sum_{f=f_l}^{f_h} fW(f)}{\sum_{f=f_l}^{f_h} W(f)} \tag{6}$$

where $W(f)$ expresses the power spectrum; $f_h$ and $f_l$ express the frequency range and were taken as $f_h = 300$ Hz and $f_l = 5$ Hz, respectively.

3) The mean power frequency of the fatigue stage 0 was normalized as 100 %.

4) The average value and standard error of 15 trials of both the lead systems were computed.

5) A Student's t-test (two-sided test) was performed between the fatigue stages of both lead systems. In this study, $p < 0.1$ was considered statistically significant.

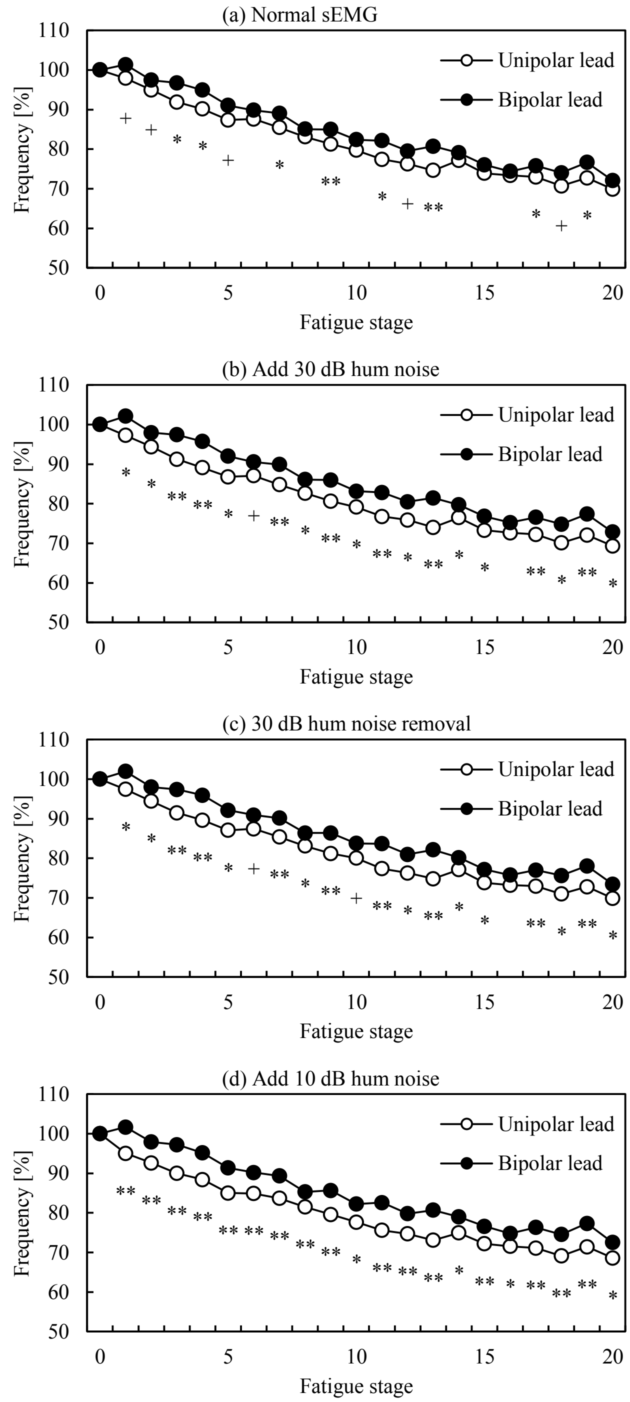
## V. RESULTS AND DISCUSSION

### *A. Re-verification of the muscle fatigue detection capability of both the lead systems by reduction of the variation in measured values.*

Figure 3 shows the normalized MPF of sEMGs detected by bipolar and unipolar lead systems with addition and removal of white noise and hum noise carried out. Using pattern (a), which added white noise, both lead systems showed an almost linear reduction from the minimum fatigue stage to the maximum fatigue stage, shown in Fig. 3(a). However, MPF measured by the unipolar-leads system was lower through all the fatigue stages. Although a statistically significant difference was not identified in some fatigue stages, the Student's t-test (two-sided test) determined a significant statistical difference from the early fatigue stage to the middle fatigue stage. This result was similar to the general trend, although the noise reduction in some stages was seen in parts where a statistically significant difference was accepted in the results of the previous study. However, because this pattern assumes a single subject, the variation in measured values was very small. Moreover, because addition of exchange noise and filtering were omitted, the muscle fatigue detection capability of a bipolar lead method was not declining. From these results, it is thought that the unipolar-leads system has excellent muscle fatigue detection capability compared with the bipolar-leads system.

### *B. Influence on the muscle fatigue detection capability by addition and removal of hum noise*

Fig. 3 (b)-(e) show the patterns with the addition and removal of hum noise. Like the pattern of Fig. 3(a), these showed an almost linear reduction in both the lead systems until a maximum fatigue stage was reached. Moreover, the unipolar-leads system, in all patterns and in all the fatigue stages, showed lower MPF values. However, compared with the pattern of Fig. 3(a), the difference between the measured MPF of each lead system was greater. The Student's t-test (two-sided test) for the patterns in Fig. 3(b) and (c), which carried out additional and removal of hum noise by $SNR = 30$ dB, showed a statistically significant difference was identified in all the fatigue stages except for fatigue stage 16. Furthermore, in the patterns in Fig. 3(d) and (e), which carried out additional and removal of hum noise by $SNR = 10$ dB, a statistically significant difference was determined for all



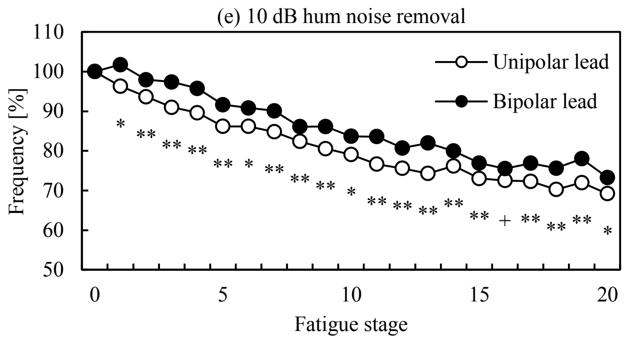



Figure 3. Normalized mean power frequency: 1 (Mean ± S. D., n = 15)
+: $p < 0.1$, *: $p < 0.05$, **: $p < 0.01$

fatigue stages. The patterns in Fig. 3(b)-(e) had many stages where a statistically significant difference was found and which showed no significant difference in Fig. 3(a). These results are more similar to the results of the previous study than Fig. 3(a) alone. The influence of the hum noise mixing was suggested due to the stages where a statistically significant difference was identified with an increase in the SNR. However, as shown in Fig. 3(b)-(e), in the patterns with the same amount of noise, there was no visible difference in the stages where a statistically significant difference was found and the stages where the difference was not significant. It is thought that the influence by filtering was minute.

In order to verify the minute influence of filtering, a Student's t-test (two-sided test) was performed between the fatigue stages of Fig. 3(a) and 3(e), where the difference between the MPF values of both the lead systems was the most remarkable (shown in Fig. 4). As a general trend, the decline in MPF was shown by both the lead systems. The result of Student's t-test (two-sided test) for the unipolar lead system showed a statistically significant difference in fatigue stages 6, 9, and 10. On the other hand, for the bipolar lead system, a statistically significant difference was found for all the fatigue stages.

These results all come from filtering and it is assumed that it is the same in the survey. However, it is thought that a unipolar lead system has a smaller filtering influence compared with a bipolar lead system. A difference between the frequency band and the peak frequency component is conjectured to be the cause, as mentioned in section I. That is, it is thought that the frequency band is narrow, however, it is large because a bipolar lead method exists where the peak frequency is in the neighborhood of 50 Hz. [ of a loss of the frequency component by filtering ].

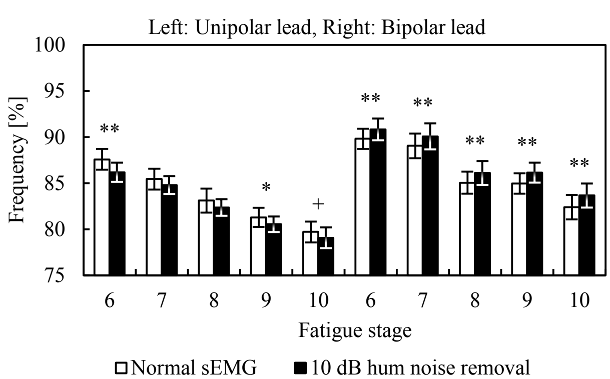



Figure 4. Normalized mean power frequency: 2 (Mean ± S. D., n = 15)
+: $p < 0.1$, *: $p < 0.05$, **: $p < 0.01$

## C. Generalization of verification result

This study compared and examined sEMG of the unipolar and the bipolar lead systems from a viewpoint of muscle fatigue detection capability, with an addition and removal of white noise and hum noise carried out in some simulations. The pattern for which addition and removal of hum noise were carried out suggested the possibility that filtering affected the muscle fatigue detection capability of the bipolar lead system. It is thought that this possibility caused a predominant result for the unipolar lead system. However, filtering had a small influence on the unipolar lead system, and it was suggested that mixing of hum noise could be disregarded. Moreover, by the pattern to which only white noise was added (Fig. 3(a)), the MPF measured by the unipolar lead system always showed a lower value compared to the bipolar lead system. Therefore, a unipolar-leads method may have high muscle fatigue detection capability regardless of the existence of or the influence of filtering. Although further examination and scrutiny are required because some of the physiological and anatomical parameters set up in this study were not based on a standard, it is thought that a unipolar lead method is equal to a sEMG survey method.

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