Estimation of Muscle Fatigue by Ratio of Mean Frequency to Average Rectified Value from Surface Electromyography

Jeffry Bonar Fernando, Mototaka Yoshioka, and Jun Ozawa

Abstract— **A new method to estimate muscle fatigue quantitatively from surface electromyography (EMG) is proposed. The ratio of mean frequency (MNF) to average rectified value (ARV) is used as the index of muscle fatigue, and muscle fatigue is detected when MNF/ARV falls below a pre-determined or pre-calculated baseline. MNF/ARV gives larger distinction between fatigued muscle and non-fatigued muscle. Experiment results show the effectiveness of our method in estimating muscle fatigue more correctly compared to conventional methods. An early evaluation based on the initial value of MNF/ARV and the subjective time when the subjects start feeling the fatigue also indicates the possibility of calculating baseline from the initial value of MNF/ARV.**

I. Introduction

Electromyography (EMG) is a technique to detect the electrical potential generated by muscle cells when they are electrically or neurologically activated. Surface EMG has been widely used since it is easy to evaluate the condition of the muscle physiologically. Three main applications of surface EMG are indicator of the initiation of muscle activation, its relationship to the force produced by a muscle, and index of muscle fatigue [1].

One major technique to estimate muscle fatigue from EMG is by assessing the time change of mean frequency (MNF) or median frequency (MDF) based on frequency analysis [1-4]. MNF or MDF is known to decrease with the increase of muscle fatigue. Oka [5] and Merletti [6] reported that besides the decrease of MNF, EMG's amplitude parameters, such as average rectified value (ARV), also increase. However, the amount for muscle fatigue cannot be quantified and fatigued and non-fatigued muscle may fall in the same range.

Yamaguchi [7], Kiryu [8], and Sasaki [9] evaluated the muscle fatigue during cycle ergometer exercise. ARV and MNF are estimated for each frame, where a frame consists of a number of EMG cycles. They proposed using time-varying behavior of correlation coefficient between ARV and MNF in a given interval, $\gamma_{\text{ARV-MNF}}$, as a muscular fatigue index. Each interval consists of L frames and is shifted by one frame from the previous interval. $\gamma_{\text{ARV-MNF}}$ will decrease from positive to negative correlation with the increase of muscle fatigue. However, to calculate correlation coefficient stably requires a long interval, which generates delay in the estimation. If the interval is shortened, the correlation coefficient may fluctuate between positive and negative. Moreover, the correlation coefficient for non-fatigued muscle may also decrease, and thus become indistinguishable with fatigued muscle.

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Sato [10] and Kushida [11] classified frequency band of EMG into three groups based on muscle fiber type. The range of type I (slow) is 20-45Hz, type IIa (intermediate) is 46-80Hz, type IIb (fast) is 81-350Hz. The sum of power spectrum for each muscle fiber type and their respective ratios are calculated. The ratio of fast muscle will decrease and the ratio of slow muscle will increase with the increase of muscle fatigue. The time when the aforementioned two ratios intersect indicates the time when the muscle is fatigued. However, this method only estimates the time of the fatigue. Moreover, the ratio of slow muscle may be larger than fast muscle from the beginning, and thus intersection does not occur. Non-fatigued muscle may also have the same tendency, and thus become indistinguishable with fatigued muscle.

In this research, a new method to estimate muscle fatigue quantitatively from EMG by using the ratio of MNF to ARV as the index is proposed. The concept of baseline is introduced to detect the time and the degree of the fatigue. Experiment results show that MNF/ARV between fatigued and non-fatigued muscle is more distinguishable compared to conventional methods. An early evaluation also indicates the possibility to calculate the baseline.

II. Methods

A. Muscle Fatigue Estimation Algorithm

Our algorithm estimates muscle fatigue by using the ratio of MNF to ARV from EMG as the index. MNF and ARV are calculated every pre-determined time or pre-determined number of cycles if the muscle contraction is periodical. MNF/ARV of non-fatigued muscle is much larger than fatigued muscle. This implies that muscle fatigue can be estimated quantitatively by our method. MNF/ARV will gradually decrease with the increase of muscle fatigue. The time when the muscle reaches its fatigue level is detected when MNF/ARV falls below a pre-determined or pre-calculated baseline. The difference between the current MNF/ARV and the baseline represents the degree of muscle fatigue.

To eliminate individual difference, we assume that the baseline can be calculated by initial value of MNF/ARV. Large initial value indicates non-fatigued muscle and the time to reach its fatigue level is longer. To make that time longer, the baseline should be decreased. Thus, we assume that baseline can be approximated in an inversely proportional equation, as shown in (1) below:

$$baseline = \frac{1}{a \times MNF(1) / ARV(1) + b}, \tag{1}$$

where MNF(1)/ARV(1) is the initial value of MNF/ARV, a and b are coefficients.

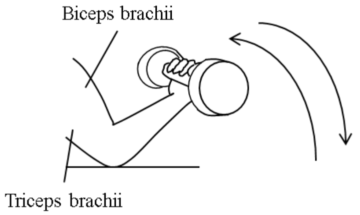

Figure 1. Experiment outline

B. Experiment

Five subjects (five males, age from 25-51) participated in the experiment. Preceding the experiment, informed consent was obtained from all subjects.

Fig. 1 shows the experiment outline. The subject holds a 5kg dumbbell in his non-dominant hand and places the elbow on a chair. The subject performs an isotonic contraction (a contraction with a change in muscle length) of biceps brachii muscle by moving his forearm up and down repeatedly with the elbow as the pivot point until he cannot lift the dumbbell any longer. The subject's posture is kept the same during the experiment. The subject is asked to inform the time when he subjectively starts feeling the fatigue and the time is recorded. Biceps brachii muscle will experience fatigue to the maximum, and thus is fatigued muscle. On the contrary, triceps brachii muscle will experience no or little fatigue since putting the elbow on the chair prevents its full contraction, and thus is non-fatigued muscle. In the end of experiment, each subject is asked whether he feels fatigue in both muscles.

While the subject is performing the task, two pairs of electrodes are attached in biceps brachii muscle and triceps brachii muscle with a distance between electrodes of 3.3cm to measure EMG of both muscles. The reference electrode and ground electrode are placed in the hip bone. EMG is measured by Polymate V AP5148, a bio-amplifier recording device. A motion sensor ZMP IMU-Z2 is placed in the subject's wrist to detect the time for each repetition of muscle contraction.

C. Evaluation

The performance of the proposed method in estimating muscle fatigue in biceps brachii muscle and triceps brachii muscle is evaluated. Besides the proposed method, experiment data are also applied to Kiryu's [8] and Kushida's [11] method for comparison. For the proposed method, MNF/ARV is calculated every three cycles of EMG. Three cycles represent three repetitions of muscle contraction, whose time range can be determined by the motion sensor. For Kiryu's method, correlation coefficient is calculated every five frames, where each frame consists of three cycles. For Kushida's method, the ratio of slow, intermediate, and fast muscle is calculated every three cycles. All three cycles are calculated with no overlaps.

An evaluation is also performed to confirm whether the baseline can be approximated from the initial value of MNF/ARV as shown in (1). In this paper, the ground truth for the baseline is the value of MNF/ARV at the reported time when the subject starts feeling the fatigue. If MNF/ARV does not exist at that time, baseline is interpolated from the existing values of MNF/ARV before and after that time.

III. Results

A. Muscle Fatigue Estimation

The experiment lasted for 182s, 546s, 248s, 129s, and 181s for subject 1-5 respectively. Subject 1, 2, 3, and 5 experienced maximum fatigue in biceps brachii muscle. Subject 4 felt pain in the forearm before the fatigue in biceps brachii muscle reached its maximum, and thus the experiment was discontinued on the way. However, subject 4 already started feeling fatigue in the biceps brachii muscle. All subjects reported to experience no or little fatigue in triceps brachii muscle. Subject 1-5 reported to start feeling the fatigue 74s, 300s, 158s, 90s, and 138s after the experiment began.

Fig. 2 shows the estimation results of muscle fatigue by Kiryu's method for each subject. Solid line and dash line represent estimation results for biceps brachii muscle and triceps brachii muscle respectively. This method assumes that

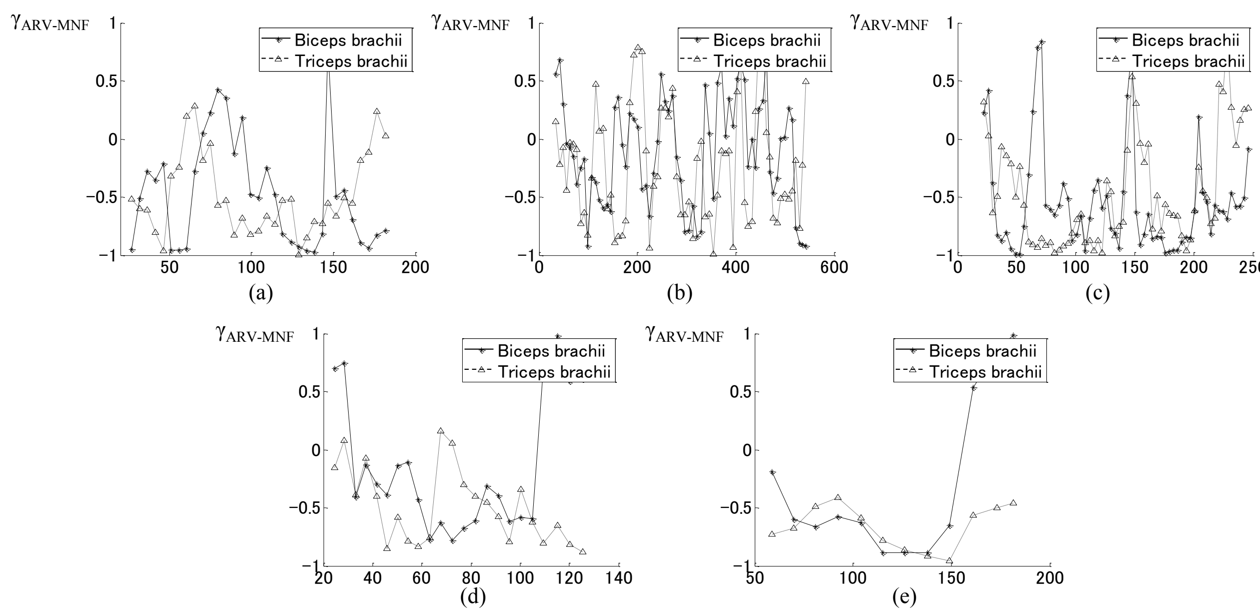

Figure 2. Estimation results by Kiryu's method (a) subject 1, (b) subject 2, (c) subject 3, (d) subject 4, (e) subject 5

the decrease of $\gamma_{\text{ARV-MNF}}$ from positive to negative indicates the increase of muscle fatigue. However, the results show that with the increase of muscle fatigue in biceps brachii muscle, $\gamma_{\text{ARV-MNF}}$ fluctuates for all subjects, which results in false estimation. Moreover, the range of $\gamma_{\text{ARV-MNF}}$ for triceps brachii muscle overlaps with the one for biceps brachii muscle. In some cases, $\gamma_{\text{ARV-MNF}}$ for triceps brachii muscle is even close to -1, which results in false estimation as fatigued muscle. Thus, this method fails to distinguish fatigued muscle and non-fatigued muscle quantitatively.

Fig. 3 shows the estimation results of muscle fatigue in biceps brachii muscle by Kushida's method for each subject. This method assumes that the intersection between the ratio of fast muscle and slow muscle indicates the time when the muscle is fatigued. The results show that the ratio of fast muscle decreases, while the ratio of slow muscle increases. However, for subject 1, 3, 4, and 5, the ratio of slow muscle is larger than fast muscle from the beginning, and thus intersection does not occur and the time of the muscle fatigue is not detected. The ratio of slow, intermediate, and fast muscle for triceps brachii muscle is in the same range with biceps brachii muscle, and thus fatigued muscle and non-fatigued muscle cannot be distinguished.

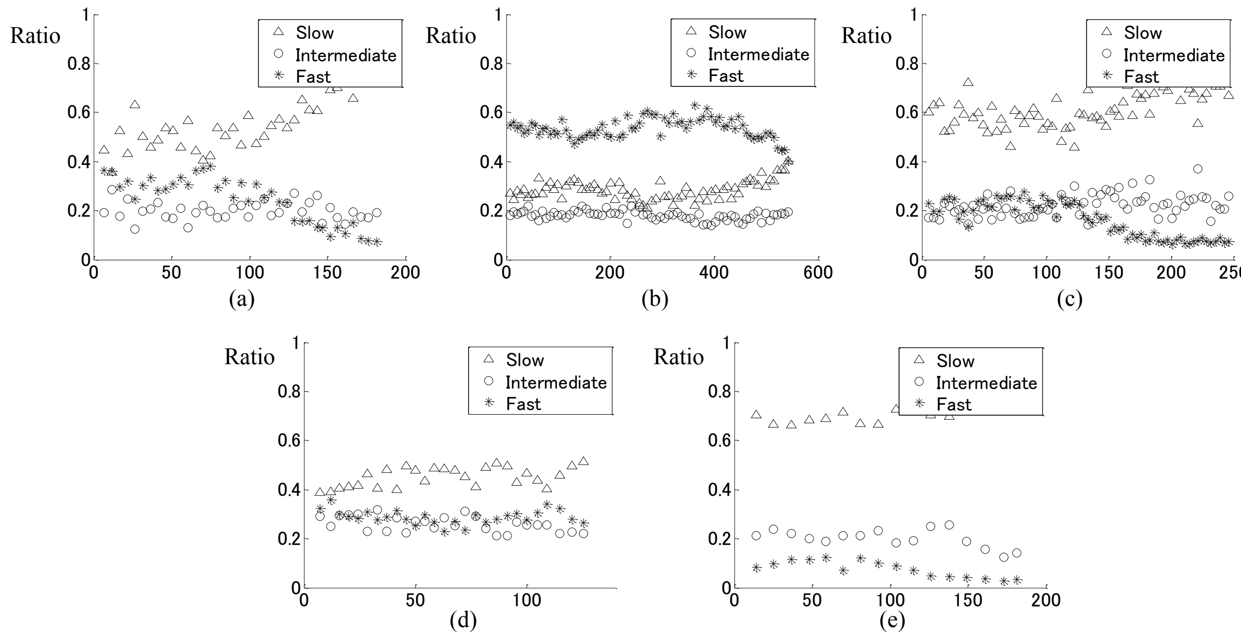

Figure 3. Estimation results for biceps brachii muscle by Kushida's method (a) subject 1, (b) subject 2, (c) subject 3, (d) subject 4, (e) subject 5

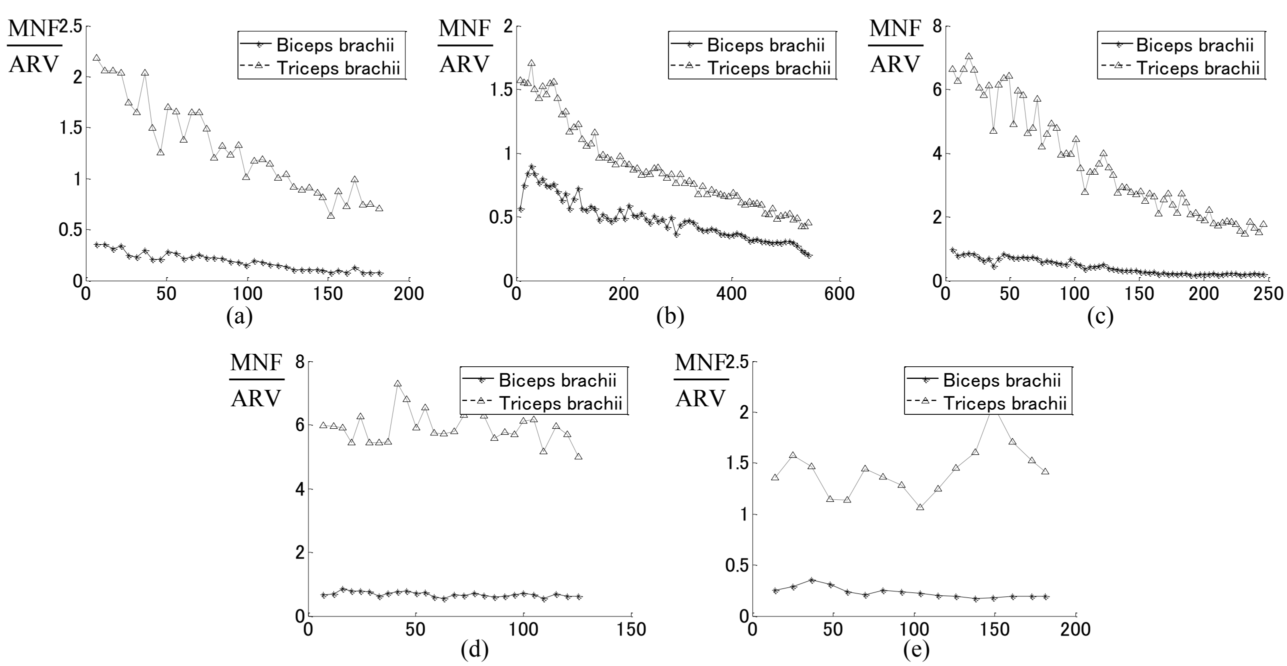

Figure 4. Estimation results by proposed method (a) subject 1, (b) subject 2, (c) subject 3, (d) subject 4, (e) subject 5

TABLE I. GRADIENT OF MNF/ARV

	Biceps brachii muscle	*Triceps brachii muscle*
Subject 1	-0.0015	-0.0080
Subject 2	-0.0010	-0.0020
Subject 3	-0.0031	-0.0226
Subject 4	-0.0012	-0.0025
Subject 5	-0.0008	0.0018

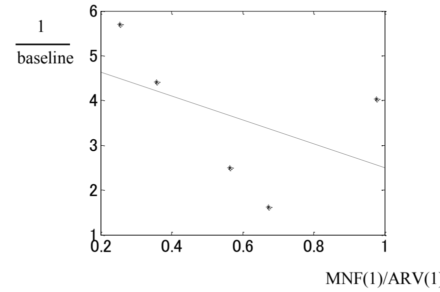

Figure 5. Relation between initial value of MNF/ARV and baseline

Fig. 4 shows the estimation results of muscle fatigue by the proposed method for each subject. Solid line and dash line represent estimation results for biceps brachii muscle and triceps brachii muscle respectively. The results show that MNF/ARV for triceps brachii muscle is larger than biceps brachii muscle, which implies that fatigued muscle and non-fatigued muscle can be distinguished quantitatively. Table I shows the gradient of time-varying MNF/ARV. For all subjects, the gradient for biceps brachii muscle is negative, while the gradient for triceps brachii muscle is either positive or negative. This shows that MNF/ARV decreases with the increase of muscle fatigue. If the baseline is set in the range of MNF/ARV for biceps brachii muscle, fatigue can be detected when its MNF/ARV falls below the baseline. In that case, triceps brachii muscle is not detected as fatigued muscle since at that time its MNF/ARV is still above the baseline.

B. *Baseline Calculation*

Fig. 5 shows the relation between initial value of MNF/ARV and the inverse of baseline for each subject. Those values are then fitted to (1) to obtain the relation equation, as shown in the dash line in Fig. 5. Although the baseline is still based on the subjective report from the subjects, the initial value of MNF/ARV and the inverse of baseline for four subjects are approximately in linear relation. This indicates the possibility of calculating baseline from the initial value of MNF/ARV.

IV. DISCUSSION

Experiment results show that fatigued muscle and non-fatigued muscle can be distinguished by our method. Further consideration on how to express the degree of muscle fatigue is required. For the experiment, only one type of weight is used. In the future, an experiment with several types of weight is required to verify our method further.

In this paper, only one initial value of MNF/ARV is used to calculate the baseline. We consider that using multiple initial values or the slope of the first multiple initial values may be more effective, and thus those assumptions need verification. Moreover, the evaluation of baseline calculation is still based on the subjective time that the subjects reported. A more objective evaluation method needs to be considered.

V. CONCLUSION

A new method to estimate muscle fatigue quantitatively from surface electromyography (EMG) by using MNF/ARV as the index is proposed. Experiment results show that the difference of MNF/ARV between fatigued muscle and non-fatigued muscle is distinctively large, and thus muscle fatigue can be estimated more correctly compared to conventional methods. We also introduce the concept of baseline to detect the time when the person starts feeling the fatigue, and thus the degree of fatigue can be evaluated quantitatively. An early evaluation indicates the possibility of calculating baseline from the initial value of MNF/ARV. Future plans include further evaluation by increasing the number of subjects, further consideration in how to calculate the baseline, and further consideration in how to quantitatively express the degree of muscle fatigue.

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