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Quantitative estimation of muscle fatigue using surface electromyography during static muscle contraction

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Abstract—**Muscle fatigue is commonly associated with the musculoskeletal disorder problem. Previously, various techniques were proposed to index the muscle fatigue from electromyography signal. However, quantitative measurement is still difficult to achieve. This study aimed at proposing a method to estimate the degree of muscle fatigue quantitatively. A fatigue model was first constructed using handgrip dynamometer by conducting a series of static contraction tasks. Then the degree muscle fatigue can be estimated from electromyography signal with reasonable accuracy. The error of the estimated muscle fatigue was less than 10% MVC and no significant difference was found between the estimated value and the one measured using force sensor. Although the results were promising, there were still some limitations that need to be overcome in future study.**

I. Introduction

Muscle fatigue is the common physiological symptom experimented by human in daily activities. This symptom is more obvious to those who perform monotonous and repetitive works, especially. Many researchers believe that muscle fatigue is one of the risk factor for musculoskeletal problem, such as occupational overuse syndrome (OOS) [1] and work-related musculoskeletal disorders (WMSDs) [2]. This problem has introduced the needs of monitoring the degree of muscle fatigue in the field of ergonomics and physiological research.

The most commonly studied technique is known as surface electromyography (SEMG). It may be due to its non-invasive and non-intrusive characteristic, which is practical for real world applications. By attaching sensors to skin above the muscle, myoelectric signal that is generated during muscle contraction can be recorded. This signal transmits through neuron to activate the motor units and eventually generates locomotion activity. During fatigue condition, the firing rate of motor unit decrease and cause the power spectrum of SEMG signal compress to lower frequency range. These changes can be measured by calculating its mean or median frequency, which is usually identified as the manifestation of muscle fatigue [3].

However, researchers also observed that frequency may increase, decrease or remain unchanged during fatigue condition [4]. This shortcoming motivated the development of other more reliable methods to index the muscle fatigue. This included frequency-band analysis [5], neural network [6], fractal analysis [7], and etc. However, these fatigue indexes only manifest the onset of muscle fatigue and not its concrete value. The main reason is because muscle fatigue itself is not a physical variable [3], therefore quantitative measurement is difficult to achieve and evaluate.

According to Vøllestad, muscle fatigue can be defined as the reduction in the maximal capacity to generate force [8]. This implies that muscle fatigue is a continuous process, which evolves over time, depending on the effort performed. During sustained muscle contraction, for instance, the maximal force that can be generated by the muscle will gradually decrease due to muscle fatigue. Based on this hypothesis, the degree of muscle fatigue can be measured, by assuming as equivalent to maximal voluntary force lost during sustained contraction tasks [9]. As a result, quantitative estimation of muscle fatigue became possible, as reported by Schwid et al. [10]. However, force sensors are commonly used when performing such diagnosis.

Based on the same principle, a method to estimate the degree of muscle fatigue using SEMG signal was proposed. In this paper, a series of static contraction handgrip tasks was performed. Then, fatigue model was first constructed based on the data captured using handgrip dynamometer. After that, we demonstrated how muscle fatigue can be estimated from SEMG signal.

II. Experimental setup

A. Subjects

Ten male students volunteered for this study. None of the subjects had a history of musculoskeletal complaints. Their mean (standard deviation) age, mass, and height were 28.9 (2.6) years, 77.5 (5.3) kg, and 173.3 (4.0) cm, respectively.

B. Experimental Procedures

The experiments were conducted in a sitting position. The chair height was adjusted so that the forearm and upper arm formed a relative angle of approximately 110 degrees. Subjects were advised to maintain their posture, especially the wrist angle, during the experiments to minimize the noise due to motion artifacts. After a short briefing, subjects were required to perform three 3-second maximal voluntary

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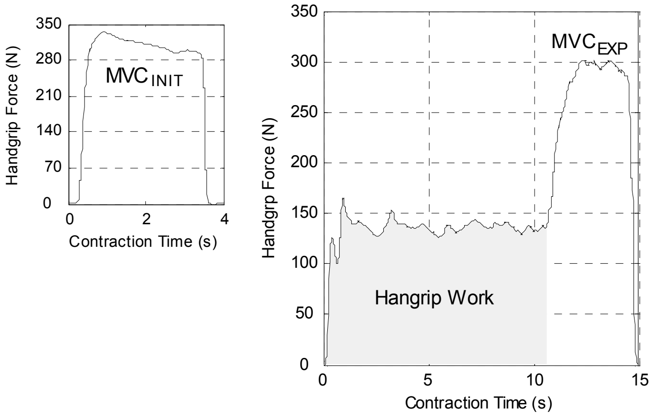

Fig. 1. Handgrip force which was captured from dynamometer during maximal voluntary contraction (left) and during static contraction task as conducted in this paper (right). Here, the MVC_{INIT} and MVC_{EXP} was recorded to calculate the force lost after performing the gripping task.

contraction (MVC) trials by exerting their maximum handgrip force. Then, the highest force level among these tests was recorded as MVC_{INIT}.

After a 15 minutes break, subjects were asked to perform a series of static contraction tasks by maintaining the force level at 50% MVC_{INIT} as steadily as possible for 10, 30, 50 and 70 seconds. An example of handgrip force was illustrated in Fig. 1. At the end of each experiment, another 3-second MVC trial was performed. This value (MVC_{EXP}) measured the remained muscle capacity after performing the gripping task. A 1-hour break was given to the subject before proceeding to the next experiments.

C. *Handgrip force measurement*

A handgrip dynamometer (Vernier Software & Technology, USA) was used to measure the force level (Newton). The sampling rate was fixed at 100 Hz, while the data was digitized at 12-bit resolution and ±0.06 N accuracy. A computer screen was located in front of each subject to display the force feedback in real time during the experiments.

D. *Surface electromyography*

SEMG data were recorded from the muscle flexor digitorum superficialis (FDS) and extensor carpi radialis (ECR) of the dominant forearm. To reduce electrical impedance between the skin and the electrode, disposable pre-gelled bipolar surface SEMG electrodes (Ag-AgCl, 10-mm diameter, GE Yokogawa Medical System, Japan) were used in this study. The center-to-center distance between two electrodes was 20 mm. The reference electrode was attached on the lateral epicondyle of the forearm. The SEMG signals were digitized using a 12-bit data acquisition card (Contec, Japan) and sampled at 1000 Hz for the subsequent computer processing.

III. Construction of Fatigue Model

A. *Definition*

In this study, we assumed that the degree of muscle fatigue is contributed by several factors, which are the amount of physical work performed, muscle recovery rate, and initial condition of the muscle. In this paper, however, the contribution due to muscle recovery and initial condition was ignored. This was based on two assumptions as explained below:

(i) This study was focused on sustained static contraction tasks; therefore the effect of muscle recovery is assumed to at its minimal level and can be ignored.

(ii) The subject was rested for one hour in between the experiment to ensure the forearm muscle is fresh (all motor unit are fully recovered) at the initial condition.

B. *Handgrip work and force lost*

The handgrip work (W) can be calculated as the generated force over contraction time [11]. Referring to Fig. 1, the total work done during this gripping task was calculated as the area under the graph,

$$W := \int_0^T f(t)\, dt \tag{1}$$

where f is the handgrip force and T is the contraction time. Then, the force lost (FL) due to the work done during the experiment was computed as,

$$FL := \frac{MVC_{INIT} - MVC_{EXP}}{MVC_{INIT}} \cdot 100 \tag{2}$$

where MVC_{INIT} and MVC_{EXP} correspond to the maximal voluntary force during the initial condition and after performing the experiment. In this study, FL was assumed to be equivalent to the degree of muscle fatigue.

C. *Fatigue model*

Motor units are the fundamental units that make up a muscle. These motor units can be categorized into several types, based on their characteristic as summarized by English and Wolf [12]. During muscle contraction, motor units are recruited orderly, from slow-twitch to fast-twitch, known as size principle recruitment strategy [13]. Based on this hypothesis, it can be concluded that during sustained muscle contraction, the degree of muscle fatigue will increase exponentially, as more fast-twitch motor units are recruited. The fatigue model that was derived by Ma et al. [14], also demonstrated similar conclusion.

Figure 2 illustrated an example of fatigue model for one subject. Here, the relationship between is FL and W, which was modeled using the exponential fit (95% confidence), was shown. The degree of muscle fatigue, was modeled as,

$$F = \alpha \cdot e^{\beta W} \tag{3}$$

where α and β are individual parameters based on the physiological condition, which is varied among subjects.

D. Computing the handgrip work from SEMG signal

Previously, we introduced the use of frequency-band technique with Continuous Wavelet Transform (CWT) in analyzing the SEMG signal [15]. It was demonstrated that handgrip force can be estimated using high frequency band. For a SEMG signal x_n with the data size N, the wavelet coefficients $C_n(s)$ for each corresponding wavelet scales (s) can be decomposed using a time-localized oscillatory function known as the mother wavelet (ψ).

$$C_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n' - n)\delta t}{s} \right] \quad (4)$$

where $0 \le n \le N-1$, δt is the sampling time, and the (*) indicated the complex conjugate [16]. The intensity of the wavelet coefficients ($E_k(s)$) was computed using root mean square (RMS) with the windows frame size of M.

$$E_k(s) = \sqrt{\frac{1}{M} \sum_{n=kM}^{(k+1)M-1} C_n(s)^2} \quad (5)$$

where $0 \le k \le \frac{N}{M} - 1$. Then, the estimated force F_k, from this SEMG signal x_n was calculated as:

$$F_k = \frac{1}{S} \sum_{s=sl}^{sh} E_k(s) R(s) \quad (6)$$

where S was the total number of wavelet scales, while sh and sl were the highest and lowest scales respectively of that frequency band. $R(s)$ was the ratio between MVC and MVE (Maximum Voluntary Electrical) activity for each corresponding wavelet scales s. In this study, the analysis was performed at the frequency range from 242Hz to 365Hz.

After that, the area under the graph, which was representing the work done by the subject, can be calculated, as in (1). This became the independent variable, for estimating the degree of muscle fatigue from the proposed model, which was constructed in previous section.

E. Performance index

The estimation error of muscle fatigue was computed as the absolute different between the estimated value (using SEMG signal) and actual force lost (measured using dynamometer). Analysis of variance (ANOVA) was used to evaluate the results and significant difference was indicated when $p < 0.05$.

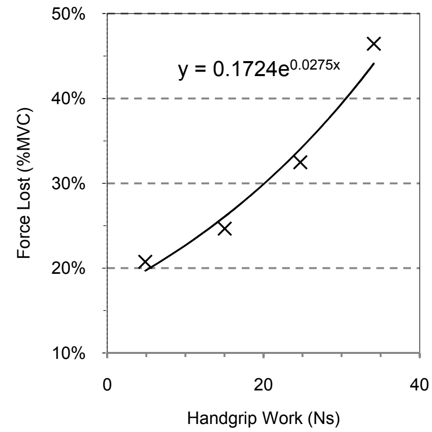

Fig. 2. An example of fatigue model for one subject, which was representing the relationship between the force lost and handgrip work. This relationship was then modeled using exponential fit.

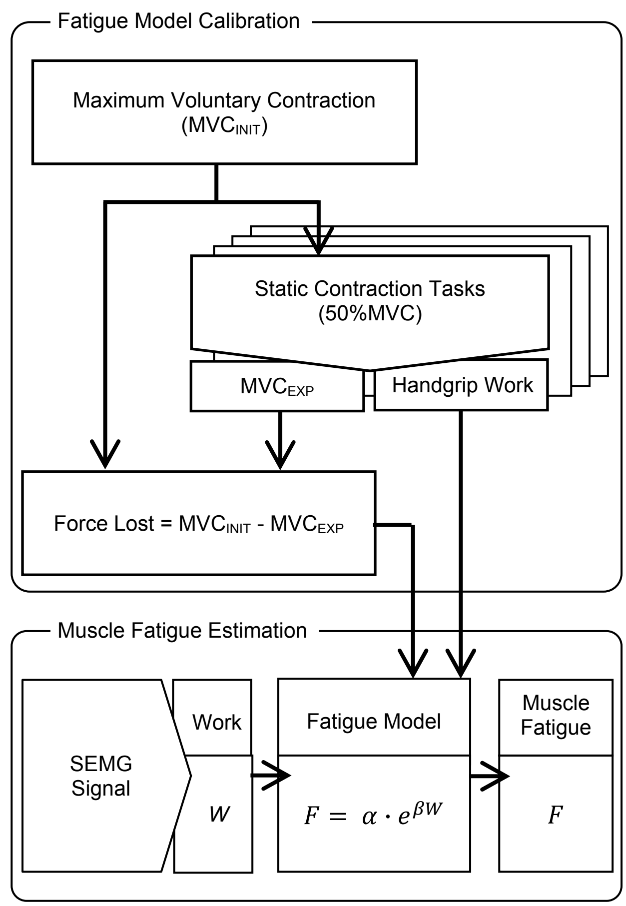

Fig. 3. The work flow of the calibration process in order to construct the fatigue model for an individual subject was shown. A series of static contraction tasks were required to model the relationship between the works done and the corresponding force lost.

IV. RESULTS AND DISCUSSION

The authors of this paper introduced a method to quantitatively estimate the degree of muscle fatigue from SEMG signal. The calibration process for fatigue model was shown in Fig. 3. A series of experiments were required in order to investigate the relationship between handgrip work and force lost. Then, the fatigue model for individual subject can be constructed. The proposed fatigue model is only valid to the contraction level where it was calibrated. This is because the development of muscle fatigue highly associated with the contraction level. Therefore, similar procedures are required to reconstruct another model before it is applied to different force level. This demerit increases the calibration complexity and limits the practicability of the proposed method. Hence, it is important to investigate the influence of contraction level on muscle fatigue. Then, a general fatigue model, which is independent of force level, can be developed.

The estimated error of the estimated muscle fatigue (mean and standard deviation) for all subjects was shown in Fig. 4. The accuracy was high for shorter contraction time (10 and 30 seconds) tasks; where the error was lower than 5% MVC. However, the performance of the proposed fatigue model slightly declined as the contraction time increased (50 and 70 seconds). As the handgrip work was the independent variable, this error can be reduced by improving the force estimation algorithm when analyzing SEMG signal.

The results showed no significant difference ($p > 0.05$) between the values estimated from SEMG signal and the one measured using dynamometer. This implied that the proposed method is reliable to estimate the degree of muscle fatigue, provided that the assumption where the total force lost is equivalent to degree of muscle fatigue still valid.

In present study, the proposed method was only applicable to static contraction tasks. This was because the effect of muscle recovery was ignored at current research stage in order to reduce the complexity of the fatigue model. However, human tasks are mostly performed in the dynamic condition, which involves changing of force level and body posture. Therefore, the effect of muscle recovery should be identified before the proposed method is applicable to real-world environment.

V. Conclusion

In this study, a fatigue model was constructed so that the degree of muscle fatigue can be estimated quantitatively from SEMG signal. The proposed fatigue model epitomized the simple relationship between the handgrip work and the force loss after performing the task. Promising results were obtained during static muscle contraction, where the error of the estimated muscle fatigue was less than 10% MVC. On top of that, no significant difference was found when comparing to the actual value, which was measured using dynamometer. However, there were still some limitations that should be overcome before it can be applied to real-world environment.

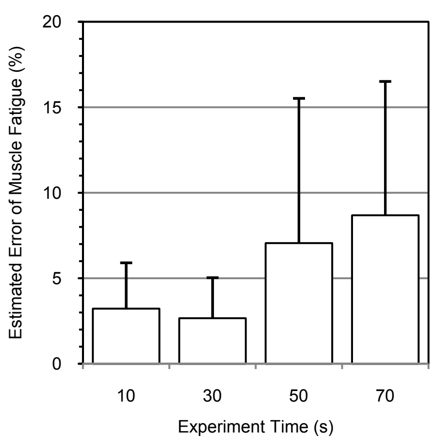

Fig. 4. Mean and standard deviation for all subjects, compared between the degrees of muscle fatigue estimated from SEMG signal and the actual value measured using dynamometer.

Acknowledgment

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