Quantification of Muscle Fatigue Using Surface Electromyography for Isometric Handgrip Task

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***Abstract*— We proposed a method to quantitatively estimate the degree of muscle fatigue by constructing a fatigue index, which represents the relationship between the force loss and handgrip work. This fatigue model allows the estimation of force loss non-intrusively using SEMG signal. Eight male subjects volunteered in this study to perform a series of isometric handgrip tasks at three different contraction levels. Handgrip work was estimated from SEMG signal, which was then used as the independent parameter for the fatigue index to estimate the force loss. The evaluation was performed by comparing the force loss that was estimated using the proposed fatigue index and the one measured from dynamometer. The average error of the estimated muscle fatigue using the proposed method was less than 10% MVC.**

***Index Terms*— Fatigue Model; Handgrip Force; Muscle Fatigue; Surface Electromyography.**

I. INTRODUCTION

Muscle fatigue is a common physiological symptom experienced by workers when carrying out their daily routines. However, prolonged exposure to fatigue conditions is hypothesized to lead to various musculoskeletal disorder problems [1, 2, 3]. These problems are often associated to the working conditions that require forceful exertion, repetitive motion and awkward body posture.

The development of muscle fatigue can be manifested by observing the power spectrum of Surface Electromyography (SEMG signal, where the Mean Frequency (MNF) decreases during the process [4, 5, 6, 7]. However, this phenomenon is used to detect the onset of muscle fatigue rather than to quantify the actual value. In fact, muscle fatigue itself is rather a subjective expression [5] and varies among individual, where its value is not measureable directly. Therefore, quantification of the muscle fatigue remains as a challenging research.

The muscle capacity in generating force decreases as the muscle fatigue developed [8]. By understanding their relationship, one could indirectly measure the degree of muscle fatigue accordingly to the losses in muscle power during contraction. Although the muscle capacity loss can be easily measured using force sensors, SEMG is better in allowing a non-invasive and non-intrusive measurement. The objective of this paper is to propose a technique to quantitatively estimate the degree of muscle fatigue from SEMG signal. Due to the complex mechanism and factors of muscle fatigue, this study is limited to the isometric handgrip tasks. First, a fatigue model was constructed using a dynamometer, and then the performance of SEMG in estimating the muscle fatigue was evaluated.

II. HANDGRIP TASKS

A. Handgrip Work

During isometric contraction tasks, no mechanical work is performed. Under this condition, handgrip work (W) is analogous to the force generated over the contraction [9]. Therefore, the handgrip work (W) can be calculated as the time integral of the contraction level,

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

where f and T are the contraction level and time, respectively.

B. Force Loss

During maximum sustained muscle contraction, for instance, the maximal force that can be generated by the muscle will gradually decrease due to muscle fatigue. This implies that muscle fatigue is a continuous process, which evolves over time and depends on the effort performed by the muscle. Based on this hypothesis, the degree of muscle fatigue can be estimated by assuming that it is equivalent to the maximal voluntary force loss during a sustained contraction task [10]. This approach, which is mainly used in clinical diagnosis for patients with muscular disorders [11], usually involves measuring the maximal voluntary force during pre-fatigue and post-fatigue conditions using a force dynamometer.

$$\Delta\mathrm{MVC} := 100 \cdot \left(1 - \frac{\mathrm{MVC_{POST}}}{\mathrm{MVC_{PRE}}}\right) \tag{2}$$

where $\mathrm{MVC_{PRE}}$ and $\mathrm{MVC_{POST}}$ correspond to the maximal voluntary force during the pre-fatigue and post-fatigue conditions of the experiment, respectively. In this study, ΔMVC is assumed to be equivalent to the degree of muscle fatigue.

III. METHOD

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

A. Apparatus and Data Collection

Subjects were seated upright with their elbow resting on an adjustable armrest and the wrist in a neutral position. The chair was adjusted so that the forearm and upper arm formed a relative angle of approximately 110 degrees.

B. Handgrip force

Handgrip force was measured using a commercial dynamometer (Vernier Software & Technology, USA). The dimension of the grip size was approximately 25 mm×45 mm. The force level was digitized at 100 Hz (12-bit resolution) and stored in a computer. A computer screen was located in front of each participant to display the force level in real time throughout the experiment.

C. Surface electromyography

The SEMG data were recorded from the muscle flex or digitorum superficialis (FDS) and extensor carpi radialis (ECR) of the dominant forearm. Disposable pre-gelled bipolar surface SEMG electrodes (Ag-AgCl, 10-mm diameter, GE Yokogawa Medical System, Japan) were used in this study to capture the SEMG signal. The center-to-center distance between the two electrodes was 20 mm. The reference electrode was attached on the lateral epicondyle of the forearm. The SEMG signals were preamplified (preamplifier gain, 90, CMMR 120 dB) and sampled at 1000 Hz using a 12-bit data acquisition card (Contec, Japan).

D. Experimental Procedures

The subjects were required to perform three experiments at 12.5% MVC, 25% MVC, and 50% MVC, which were denoted as E12, E25, and E50, respectively. These experiments were conducted in three separate days. Each experiment consists of four handgrip tasks that were performed at the same contraction level but with different contraction times. The sequence of these handgrip tasks was randomized for each subject. Figure 1 shows the summary of the experiments and handgrip tasks that were conducted. The experimental procedures are explained in detail below.

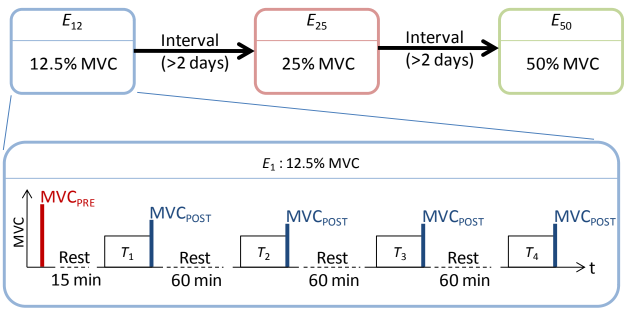

Figure 1: Three experiments were conducted at different contraction level: 12.5%, 25%, and 50% MVC. Each experiment consists of four handgrip tasks, which were performed at same contraction level but different contraction time.

Each experiment began with a MVC trial, in which the subjects were required to exert their maximum handgrip force for 3 seconds. The highest force level within the trial was then recorded as pre-fatigue MVC (MVCPRE). After a 15-minute break, the subjects continued the experiment with four isometric handgrip tasks. For each handgrip task, the subjects were instructed to maintain the contraction level by tracing the guideline displayed on the screen. At the end of the handgrip task, another 3-second MVC trial was measured. The value was recorded as MVCPOST. It represented the remaining muscle capacity left after performing the task. After rested for 1-hour, similar handgrip task was repeated at the same contraction level but with different contraction times. The detail of the experiments and the corresponding handgrip tasks are listed in Table 1.

Table 1
Experimental Procedures

Experiment	Task	Contraction level (%MVC)	Contraction Time (s)
	T_1		40
E_{12}	T_2	12.5%	120
	T_3		200
	T_4		280
	T_1		20
E_{25}	T_2	25%	60
	T_3		100
	T_4		140
	T_1		10
E_{50}	T_2	50%	30
	T_3		50
	T_4		70

E. Proposed Method

The overview of the proposed method is shown in Figure 2. Firstly, the SEMG signal was recorded from the forearm muscle. This signal was used to estimate the handgrip force generated by the muscle. Then, the handgrip work can be calculated, which is used as the independent parameter for the fatigue model. The fatigue model represents the relationship between the handgrip work and force loss.

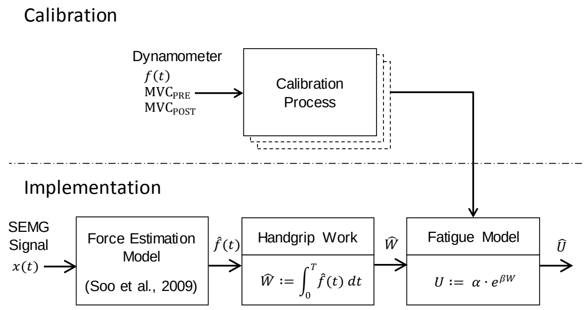

Figure 2: Overview of the proposed method for quantifying the degree of muscle fatigue using SEMG signal.

F. Fatigue Model

The rate of muscle fatigue developed during muscle contraction varies with the contraction level (*f*). Therefore, the fatigue model in Eq. (3) is developed with the relationship with its contraction level.

$$U_f := a \cdot exp\{bf + (cf + d)W\} \tag{3}$$

where

$$\alpha := a \cdot e^{bf} \tag{4}$$

$$\beta := cf + d \tag{5}$$

G. Estimation of muscle fatigue using SEMG signal

Once the fatigue model is calibrated using the dynamometer, the degree of muscle fatigue can be estimated from SEMG signal. This is performed by estimating the handgrip work (W) as the independent variable of the fatigue model indirectly from the SEMG signal. The handgrip work is computed as the area under the graph of estimated handgrip force (f) as stated in Eq. (1), in which $f(t)$ is obtained from the SEMG signal using the frequency-band analysis [15].

H. Fatigue Index

The muscle fatigue estimates from the calibrated fatigue index is compared to the force loss measured using the dynamometer for each experiment (E12, E25, and E50). The estimation error ε is computed as,

$$\varepsilon := \left|\Delta MVC - \widehat{U}\right| \qquad (6)$$

where $\widehat{U}$ is the degree of muscle fatigue estimated from the proposed fatigue index, ΔMVC is the force loss measured using dynamometer.

IV. RESULT

A. Proposed Method

A sample of the experimental result and the calibrated fatigue model (U_f) is illustrated in Figure 3. The graph represents the force loss measured with a dynamometer for four handgrip tasks, as conducted in experiment E_1. These data are used to calibrate the fatigue model for each subject. The calibration process is essential, as the physiological condition for each individual subject is different. This is done by fitting the function of the fatigue model as stated in (3) to identify the variables (a, b, c and d).

Use SI as primary units. English units may be used as secondary units (in parentheses). For example, write "15 Gb/cm^2 (100 Gb/in^2)." An exception is when English units are used as identifiers in trade, such as "3½-in disk drive." Avoid combining SI and CGS units, such as current in amperes and magnetic field. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., "A·m^2."

After the calibration process, we can generate a fatigue profile with a different contraction level by varying the contraction level (f) and the contraction time (t). The fatigue profile as illustrated in Figure 4 is generated by using the proposed fatigue model for a subject. With this fatigue profile, the degree of muscle fatigue can be estimated as long as the handgrip force and the contraction time are provided.

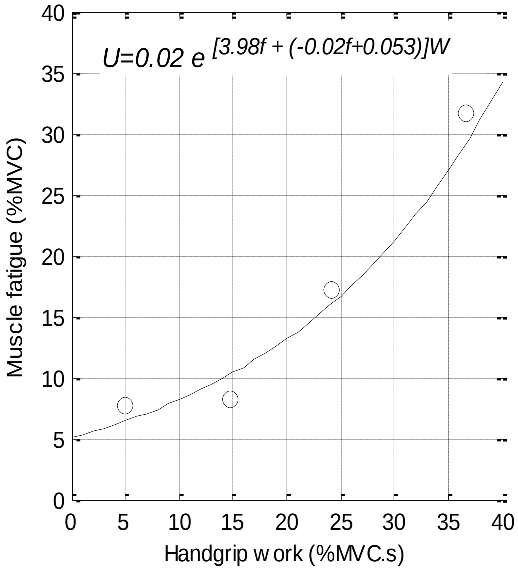

Figure 3: The fatigue model calibrated accordingly to the force loss measured with a dynamometer.

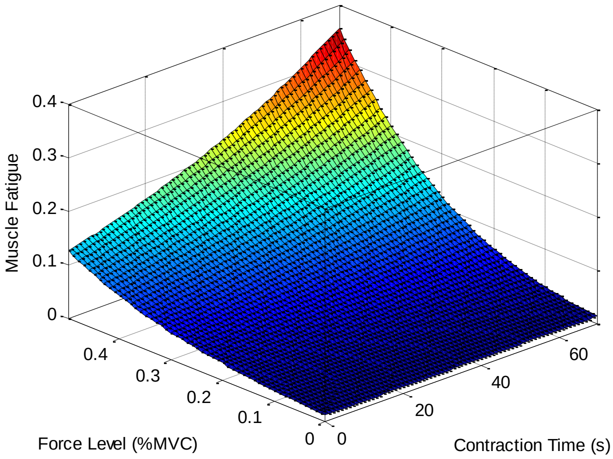

Figure 4: Fatigue profile generated using the fatigue model for one subject. The degree of muscle fatigue can be estimated by calculating the handgrip force and contraction time.

B. Estimation of muscle fatigue using SEMG signal

After the fatigue model is constructed, we can quantitatively estimate the degree of muscle fatigue from the SEMG signal. This was performed by estimating the handgrip force from the SEMG signal. In total, three experiments (E12, E25, and E50) were carried out to evaluate the accuracy of the proposed method. These experiments were conducted at 12.5% MVC, 25% MVC, and 50% MVC, which represents low, medium, and high levels of contraction, respectively. Each experiment consists of four handgrip tasks with varying contraction times. The duration is varied to achieve a similar amount of handgrip work at the desired contraction level.

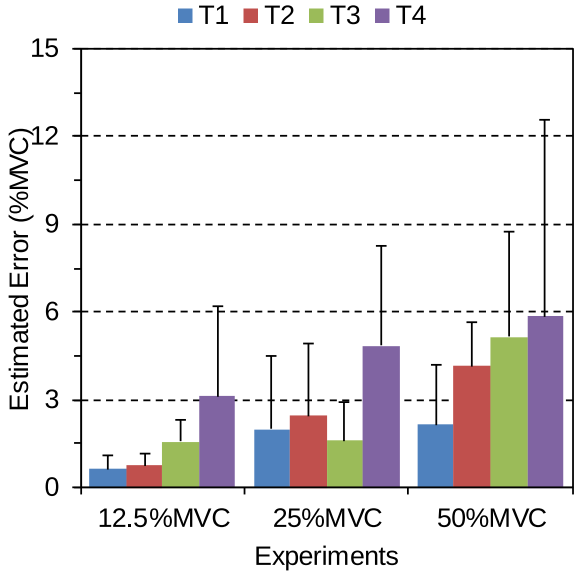

Figure 5: Mean and standard deviation for all subjects compared between the degrees of muscle fatigue estimated from the SEMG signal and the actual value measured using a dynamometer.

The average error of the estimated muscle fatigue (mean and standard deviation) for all subjects is shown in Figure 5. In general, the average estimated error for all the experiments achieves our expectation, which is lower than 10% MVC. The accuracy declines slightly when the contraction time increases (comparing T1 and T4). Because it is difficult to measure the actual degree of muscle fatigue directly, we can only compare the estimated value to the force loss measured using a dynamometer. In this context, the result of the present paper is valid providing that the subjects are performing the task at their best effort, especially during the MVC trials. Figure 5 also illustrates the results for each fatigue model introduced in this study.

Since the fatigue model is correlated to the handgrip work, the performance of the proposed technique is solely dependent upon the force level estimated from the SEMG signal. Figure 6 illustrates the average error (mean and standard deviation) of the handgrip work and compares the value calculated using the force level measured with a dynamometer and that estimated from the SEMG signal.

The error of the estimated muscle fatigue can also be caused by other factors. For example, it may due to mental fatigue. It was previously demonstrated that mental fatigue reduces the force-generating capacity. An approximately 20% of MVC reduction is expected due to mental fatigue during a sustained maximum voluntary static contraction. This affects the MVCPOST measured at the end of each experiment, where the value becomes lower than it should be. In this study, visual feedback and verbal motivation [16] were provided during the experiment to ensure that the subject made his best effort, especially during the MVC trial. Another possible explanation may be that the longer contraction time at a constant posture reduces the blood flow, which becomes a factor for muscle fatigue [17]. This will also cause pain and discomfort to the subjects due to the pressure between the palm and the dynamometer. The subject will be indirectly affected as he generates maximum force at the end of the contraction task. Such a situation becomes more obvious with a longer contraction time, as shown in Fig. 5. In summary, there are various factors that will cause a subject to not exert a true MVC value during post-fatigue. With the current experimental setup, this problem is difficult to correct; however, it can be overcome using electric muscle stimulation [18] instead of personal effort during an MVC trial.

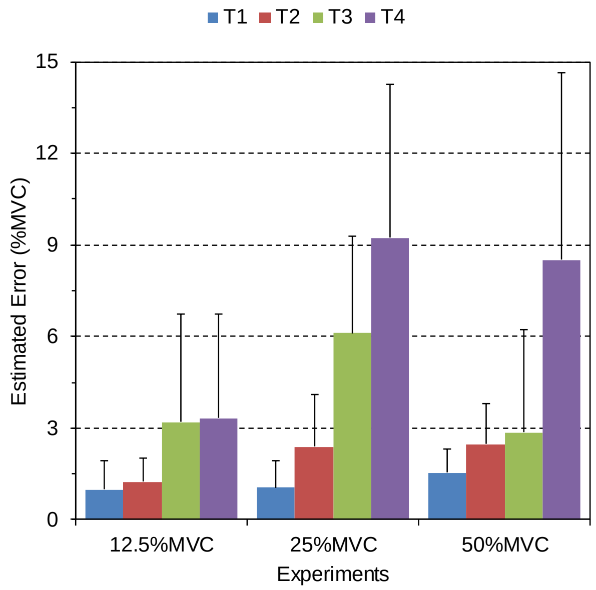

Figure 6: Error (mean and standard deviation) of the handgrip work calculated using the handgrip force measured with a dynamometer and that estimated from the SEMG signal.

V. DISCUSSION

In this study, muscle fatigue is interpreted as a physical variable that increases over time during sustained contractions. This variable is expressed as an exponential-based function that is associated with the contraction level and duration. A similar exponential fatigue model has been reported elsewhere [12, 13, 14]. Ma et al. [14] proposed a fatigue model from the viewpoint of the muscle capacity and external load. The muscle capacity that is lost after sustained muscle contraction is used as an index for muscle fatigue. These researchers demonstrated that, during an isometric task, muscle fatigue increases exponentially. Their simulation results verify the validity of an exponentially derived fatigue model in comparison to other existing models. Deeb et al. [13], on the other hand, introduced a bi-exponential model to estimate muscle capacity after endurance time during an isometric contraction task. The two exponential expressions correspond to a different rate of fatigue for slow-twitch and fast-twitch muscle fibers.

The discrepancy between the present study and others could be attributed to the way in which the individual parameters are defined, including their relationship to the contraction level. The fatigue model that was introduced in this study is expressed in a single exponential term, which is identical to that proposed by Ma et al. [14]. Regardless of the fatigue model, the main contribution of this study is the quantitative estimation of muscle fatigue using the SEMG signal. The fatigue model in this study is the function that represents the relationship between the force loss and handgrip work. Therefore, in this paper, it is not our intention to identify the best model to be utilized. In addition to the exponential-based function, the fatigue model can also be found in other expressions [19, 20]. We believe that the proposed technique is also applicable to these fatigue models and is not limited exclusively to an exponential function.

The causes of muscle fatigue are complicated and not thoroughly understood due to its multi-factorial etiology, psychological factors, and patient perceptions [21]. In general, the degree of muscle fatigue depends on several factors, which are the amount of physical work performed, muscle recovery rate, and initial condition of the muscle. In order to reduce its complexity, in this paper, we assume that the physical work performed is the only factor of muscle fatigue. For a sustained static contraction, especially at a higher contraction level, the muscle recovery during the contraction is not significant [22].

VI. CONCLUSION

In this paper, we introduced a method to quantitatively estimate the degree of muscle fatigue from the SEMG signal. This method is based on the relationship between the handgrip work performed by the muscle and the maximal voluntary force loss. Promising results were obtained during isometric muscle contraction, in which the average error of the estimated muscle fatigue was less than 10%MVC. An understanding of the mechanism behind muscle fatigue is beneficial in various applications, such as ergonomics and rehabilitation studies. Quantitative estimation of muscle fatigue will allow the monitoring of the muscle condition in a working environment and prevent unnecessary muscular injuries.

ACKNOWLEDGMENT

This research was partially supported by Special Coordination Funds for Promoting Science and Technology, the "IRT Foundation to Support Man and Aging Society," and the Global COE Program "Global Center of Excellence for Mechanical Systems Innovation," MEXT, Japan.

REFERENCES

[1] Salvendy, G. 1997. Handbook of Human Factors and Ergonomics. New York: Wiley.

[2] Kishi, R., T. Kitahara, A. Masuchi, and S. Kasai. 2002. Work-related Reproductive, Musculoskeletal and Mental Disorders among Working Women-History. Current Issues and Future Research Directions. Industrial Health. 40(2): 101-112.

[3] Podniece, Z. 2008. Work-related Musculoskeletal Disorders: Prevention Report (A European campaign on musculoskeletal disorder). Belgium: Office for Official Publications of the European Communities.

[4] Allison, G., and T. Fujiwara. 2002. The Relationship Between EMG Median Frequency and Low Frequency Band Amplitude Changes at Different Levels of Muscle Capacity. Clinical Biomechanics. 17(6): 464-469.

[5] Merletti, R., and P. Parker. 2004. Electromyography: Physiology, Engineering, and Noninvasive Applications. New York: Wiley-IEEE Press.

[6] Yassierli and M.A. Nussbaum. 2008. Utility of Traditional and Alternative EMG-based Measures of Fatigue During Low-Moderate Level Isometric Efforts. Journal of Electromyography and Kinesiology.18(1): 44-53.

[7] Chowdhury, S.K., A.D. Nimbarte, M. Jaridi, and R.C. Creese. 2013. Discrete Wavelet Transform Analysis of Surface Electromyography for The Fatigue Assessment of Neck and Shoulder Muscles. Journal of Electromyography and Kinesiology. 23(5): 995–1003.

[8] Vøllestad, N. 1997. Measurement of Human Muscle Fatigue. Journal of Neuroscience Methods. 74(2): 219-227.

[9] Bautmans, I., E. Gorus, R. Njemini, and T. Mets. 2007. Handgrip Performance in Relation to Self-Perceived Fatigue, Physical Functioning and Circulating IL-6 in Elderly Persons Wthout Inflammation. BMC Geriatrics. 7(1): 5.

[10] Zwarts, M.J., G. Bleijenberg, and B.G. van Engelen. 2008. Clinical Neurophysiology of Fatigue. Clinical Neurophysiology. 119(1): 2-10.

[11] Schwid, S., C. Thornton, S. Pandya, K. Manzur, M. Sanjak, M. Petrie, M. McDermott, and A. Goodman. 1999. Quantitative Assessment of Motor Fatigue and Strength in MS. Neurology. 53(4): 743-743.

[12] Rohmert, W. 1973. Problems in Determining Rest Allowances Part 1: Use of Modern Methods to Evaluate Stress and Strain in Static Muscular Work. Applied Ergonomics. 4(2): 91-95.

[13] Deeb, J.M., C.G. Drury, and D.R. Pendergast. 1992. An Exponential Model of Isometric Muscular Fatigue as A Function of Age and Muscle Groups. Ergonomics. 35(7): 899-918.

[14] Ma, L., D. Chablat, F. Bennis, and W. Zhang. 2009. Dynamic Muscle Fatigue Evaluation in Virtual Working Environment. International Journal of Industrial Ergonomics. 39(1): 211-220.

[15] Soo, Y., M. Sugi, H. Yokoi, Y. Arai, M. Nishino, R. Kato, T. Nakamura, and J. Ota. 2009. Estimation of Handgrip Force using Frequency-Band Technique During Fatiguing Muscle Contraction. Journal of Electromyography and Kinesiology. 20(5): 888-895.

[16] Campenella, B., C.G. Mattacola, and I.F. Kimura. 2000. Effect of Visual Feedback and Verbal Encouragement on Concentric Quadriceps and Hamstrings Peak Torque of Males and Females. Isokinetics and Exercise Science. 8: 1-6.

[17] Søgaard, K. 1995. Motor Unit Recruitment Pattern During Low-Level Static and Dynamic Contractions. Muscle & Nerve. 18(3): 292-300.

[18] Chen, J.J., and N. Yu. 1997. The Validity of Stimulus-Evoked EMG for Studying Muscle Fatigue Characteristics of Paraplegic Subjects During Dynamic Cycling Movement. IEEE Transactions on Rehabilitation Engineering. 5(2): 170-178.

[19] Merletti, R. 1991. Indices of muscle fatigue. Journal of Electromyography and Kinesiology. 1(1): 20-33.

[20] Cairns, S.P., D.M. Robinson, and D.S. Loiselle. 2008. Double-Sigmoid Model for Fitting Fatigue Profiles in Mouse Fast- and Slow-twitch Muscle. Experimental Physiology. 93(7): 851-862.

[21] Fitts, R. 1981. Cellular Mechanisms of Muscle Fatigue. Physiological Reviews. 74(1): 49-94.

[22] Wilson, J., and E. Corlett. 2015. Evaluation of Human Work: A Practical Ergonomics Methodology. Florida: CRC Press.