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Prediction of biceps muscle fatigue and force using electromyography signal analysis for repeated isokinetic dumbbell curl exercise[†]

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Abstract

In this study, a new way to predict the muscle fatigue and force from Electromyography (EMG) signal for repeated isokinetic exercise is demonstrated. The relationship between cumulative biceps fatigue and EMG signal during repetitive dumbbell curl tasks with constant velocity was investigated with respect to Maximum voluntary contraction (MVC) levels (20 %, 35 %, 50 % and 75 % MVC). The mean integrated EMG and mean frequency per cycle were obtained from the time domain and frequency domain, respectively. The mean IEMG value and mean frequency values were co-plotted in the global EMG index map. Finally, we developed a new algorithm to predict muscle fatigue and force based on a global EMG index map employing mean IEMG and MNF values. The proposed algorithm based on a global EMG index map can be used to simultaneously predict muscle fatigue and force from real-time EMG signals with arbitrary MVC levels.

Keywords: Muscle fatigue; Electromyography (EMG); Integrated EMG (IEMG); Mean frequency

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1. Introduction

Evaluation of muscle strength and fatigue is of interest due to the importance of muscle function in sports activities and overall functional capacity. Therefore, it is necessary to quantitatively evaluate muscle force and fatigue of workers and athletes in order to improve safety and efficiency as well as to prevent musculoskeletal disorders. The term muscle fatigue is used to denote a transient decrease in the capacity to perform physical actions [1-4]. Muscle fatigue describes the gradual decrease in force capacity of muscles or the endpoint of a sustained activity, and the onset of muscle fatigue is typically quantified as a decline in the maximal force of power capacity of muscle. Most investigators invoke a more focused definition of muscle fatigue as an exercise-induced reduction in the ability of muscles to produce force or power regardless of whether or not the task can be sustained [5, 6]. Much is known about the physiological impairments that can cause muscle fatigue. Specifically, fatigue can be caused by many different mechanisms, ranging from the accumulation of metabolites within muscle fibers to the generation of inadequate commands in the motor cortex.

Surface Electromyography (EMG) can be utilized in the analysis of muscle activity and can be applied to assess muscle fatigue or endurance time when the muscle is no longer capable of sustaining submaximal voluntary muscle force [7-9]. EMG is based on changes in amplitude and frequency, which can be used to classify the level of electrical activity associated with a specific degree of muscular tension. Changes in myoelectric signals are based on the recruitment and firing rates of motor units within muscle. The interpretation of the changes in recruitment and firing rate can provide information concerning the degree of force exerted by a muscle and its degree of fatigue. Specifically, information regarding muscle force and fatigue can be obtained from time domain analysis and frequency domain analysis, respectively [10, 11]. The basic information obtained from the time domain analysis (e.g. Integrated EMG (IEMG) and Root mean square (RMS)) comprises 1) whether or not the muscle is active and 2) the relative amount of activity of the muscle. Meanwhile, in the frequency domain analysis (e.g. Mean power frequency (MNF) and Median frequency (MDF)), fatigue information can be discerned by analyzing frequency shift phenomenon.

EMG recorded during voluntary muscle contracting exercises has been extensively studied in order to determine its relationship with muscle force [12-15] and muscle fatigue [16-

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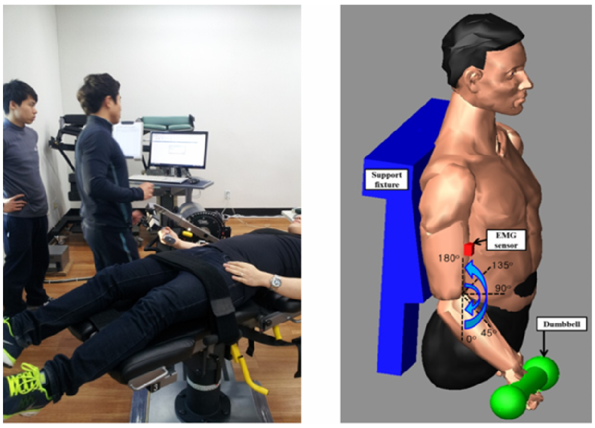
19]. The notion that the magnitude and intensity of the EMG signal is at least qualitatively related to the force produced by a muscle under given condition is well accepted in the scientific community [15]. Meanwhile, muscle fatigue is generally accompanied by an increase in the Root mean square (RMS) of the EMG [16], because it involves the concurrent firing rates of all active motor units. In the frequency domain, decreases in the action potential conduction velocity shifts the EMG Power density spectrum (PDS) toward lower frequencies during both static and dynamic contractions throughout prolonged submaximal contractions [17-19].

As mentioned above, analysis of EMG signals can be generally divided into two main areas, i.e., muscle force and muscle fatigue. However, there is currently no global EMG index that can be applied for simultaneous determination of muscle fatigue and muscle force prediction. Therefore, in this paper, we suggest a new global EMG index map based on the combination of mean frequency (MNF) and mean integrated EMG (mean IEMG) data, which can be used to simultaneously predict muscle force and fatigue. Specifically, we investigated the relationship between the cumulative fatigue of the biceps muscle and EMG signal during a repetitive dumbbell curl task performed at constant velocity (3 sec cycle time) with respect to Maximum voluntary contraction (MVC) values (20 %, 35 %, 50 %, and 75 % MVC). The integrated EMG and mean frequency were obtained from the time domain and the frequency domain signal analysis, respectively, for different repetitive MVC conditions. The mean IEMG was obtained by dividing the Integrated EMG values by cycle time (IEMG/time). The mean IEMG value and mean frequency values were co-plotted together as the global EMG index map and their relationships with muscle fatigue and force were investigated.

2. Methods

2.1 Subjects

Fifteen healthy male volunteers with no history of cardiovascular, neurological, or upper limb disorders, provided written informed consent to participate in this study, which was approved by the Hanyang University Institutional Review Board. Each subject was informed of the purpose of the study before consent was obtained. The mean (SD) age, height and body mass of the subjects were 26.4 (3.4) years, 174.7 (3.1) cm and 74.8 (3.5) kg, respectively. The Maximum voluntary contraction (MVC) torque for each subject was measured using dominant (right) elbow flexion with a Cybex isokinetic dynamometer (Cybex, Humac/Norm 502140) prior to isokinetic exercise [20]. As shown in Fig. 1(a), the MVC torque was measured at below fist level and the force output was displayed on a screen, allowing the subjects to obtain immediate feedback. Prior to determination of Maximal voluntary contraction (MVC), a 5 min isometric warm-up was performed. The warm-up period consisted of three sets of short (5 sec.) submaximal elbow flexors, with each set followed by a 1 min rest period. MVC torque was defined as the highest torque produced during three successive contractions.



(a) (b)

Fig. 1. Schematics of the MVC test employing a Cybex isokinetic dynamoneter for measuring MVC torque (a); elbow flexion exercise protocol (b).

2.2 Exercise protocol: isokinetic exercise

The isokinetic exercise protocol consisted of four different load tasks ranging from light to heavy loads. In this study, weights corresponding to 20 %, 35 %, 50 %, and 75 % of each subject's MVC were used. Each subject was asked to stand erect with their upper arm fixed, and then directed to move their lower arm through a full range of motion in the sagittal plane at a speed of 20 repetitions per minute (3 sec/cycle) using a metronome (Fig. 1(b)). To evaluate muscle fatigue, the subjects continued the exercise until they could no longer follow the speed of the metronome. The subjects took at least one week of rest between subsequent exercise routines to avoid the fatigue effect. EMG (TeleMyo 2400T, Noraxon Inc.) signals were recorded from the biceps brachii using Ag-AgCl wet-gel bipolar surface electrodes (2 cm apart, diameter: Smaller than 1 cm). Prior to electrode placement, the skin was shaved and cleansed with alcohol. The bipolar electrode was placed on the area of greatest muscle bulk along the longitudinal midline of the muscle, which was selected based on the "Surface EMG for non-invasive assessment of muscles (SENIAM)" [21].

2.3 Signal processing

Signals obtained from the EMG amplifier were sent to a host PC at a sampling rate of 1500 Hz. All data obtained from the subjects were consecutively segmented using a cycle time window of 3 seconds (one contraction cycle time). The segmented EMG signals were analyzed in terms of time and frequency domains. For frequency domain analysis, Fast Fourier transform (FFT) was performed for each windowed segment in order to estimate the power spectrum used to calculate the

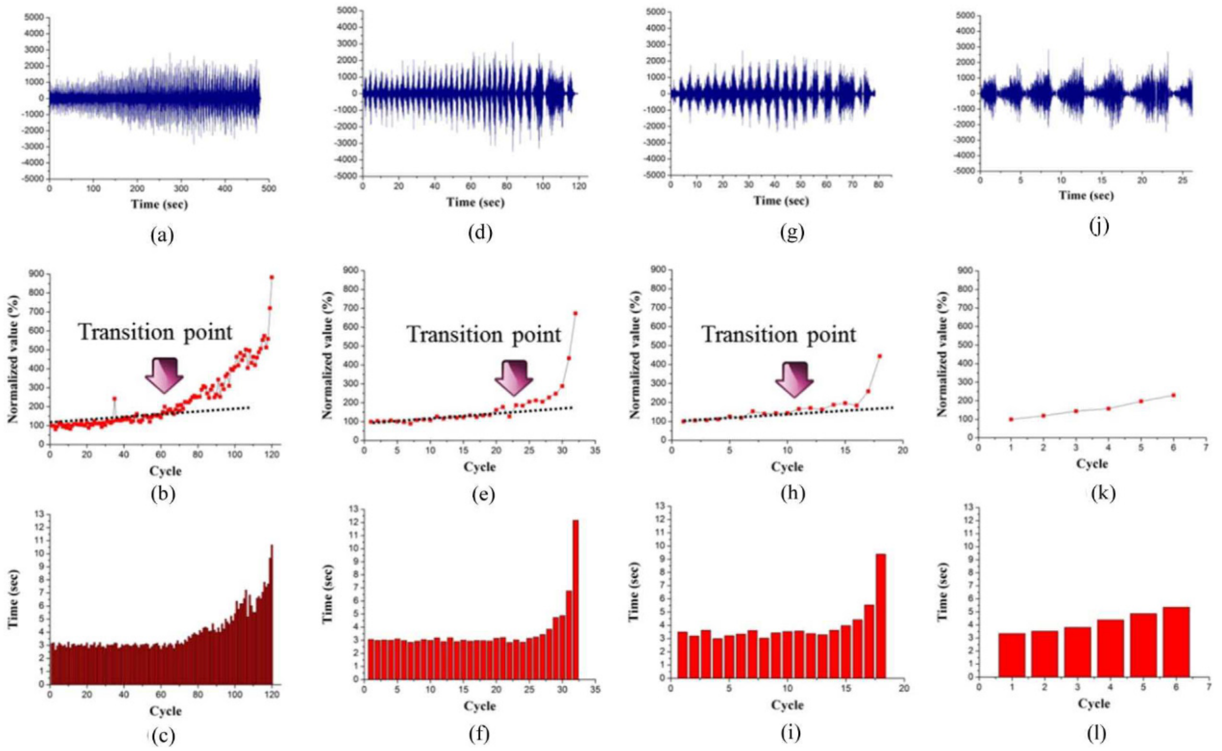


Fig. 2. EMG signals (a, d, g, j); mean EMG value (b, e, h, k); cycle times (c, f, i, l) during the cyclic dynamic contractions of biceps brachii muscle for different loads (20 %, 35 %, 50 % and 75 % MVC).

MNF (Mean power frequency) [22, 23]. MNF can be expressed as

$$\mathrm{MNF} = \sum_{j=1}^{M} f_j P_j \quad \sum_{j=1}^{M} P_j \tag{1}$$

where fj is the frequency value at a frequency bin j.

Meanwhile, the Integrated EMG (IEMG) was calculated to estimate the amount of muscle activity. Integration refers to the mathematical operation of computing the area under the curve. Because the integral of the raw EMG is zero, it is necessary to full-wave rectify the raw signal in order to obtain an absolute value [11, 24]. This operation can be expressed as follows:

$$\mathrm{I}\left\{EMG(t)\right\} = \int_{0}^{t} \left|EMG(t)\right| dt \tag{2}$$

As is evident from the formula, the integral will increase continuously as a function of time. In practical integrator designs, the time period must be limited because of the limited dynamic range of the integrator circuit. This is typically accomplished by integrating over a fixed time interval. In such cases, the operation is expressed as follows:

$$\mathrm{I}\left\{EMG(t)\right\} = \int_{t}^{t+T} \left|EMG(t)\right| dt \tag{3}$$

where T is the suggested cycle time (3 sec). In this study, in order to account for the cycle time of isokinetic tasks, the Integrated EMG (IEMG) value of each cycle was normalized by dividing each IEMG value by its corresponding cycle time as shown below. The normalized IEMG values were expressed as "Mean IEMG" as below:

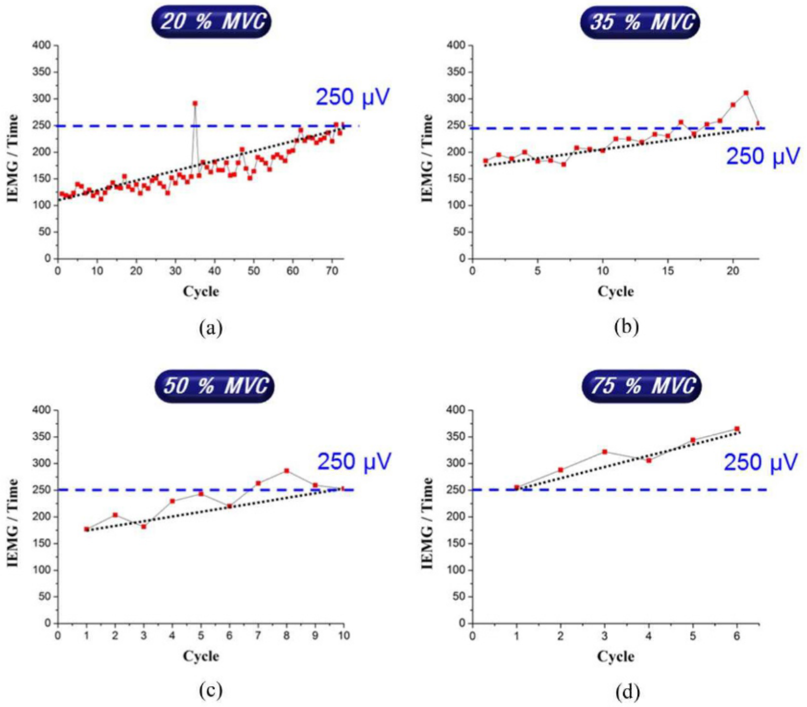
$$\text{Mean IEMG} = \ \mathrm{I}\left\{EMG(t)\right\}_j \quad time_{cycle,\,j} \tag{4}$$

where $IEMG(t)_j$ and $time_{\text{cycle, j}}$ are the IEMG value and cycle time of each cyclic dynamic contraction task, respectively.

3. Results and discussion

Fig. 2 shows the EMG signals, mean IEMG values, and cycle time of cyclic dynamic contractions with different load conditions (20 %, 35 %, 50 % and 75 % MVC). We found that the amplitude of EMG in pre-fatigued muscles increased as MVC value increased (refer to the EMG amplitude at the first cycle in each Figs. 2(a), (d), (g) and (j)), which was attributed to the EMG-force relationship. Previous studies have shown that force enhancement in pre-fatigued muscle is due to the recruitment of regularly larger faster twitch fibers with larger conduction velocity [25]. Therefore, it is reasonable to expect that the higher EMG amplitude at higher MVC level exercise was due to both increased motor unit recruitment and a higher firing rate during higher levels of force exertion.

The amplitude of EMG signals increased with accumulating

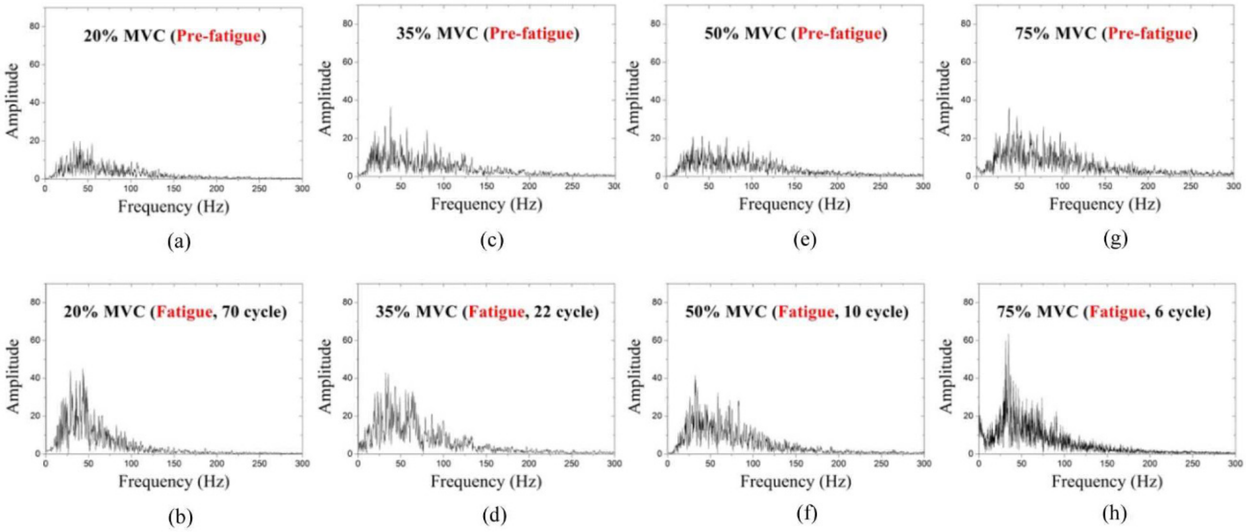


(a) (b) (c) (d)

Fig. 3. Mean IEMG (IEMG/time) values of biceps brachii muscle during cyclic dynamic contractions for different loads (20 %, 35 %, 50 % and 75 % MVC).

muscle fatigue (i.e. as the number of dumbbell curl exercise cycles increased) as shown in Figs. 2(a), (d), (g) and (j). In general, the amplitude of EMG signals was also closely associated with the accumulation of fatigue in the muscle [17, 26, 27]. Fatigue causes reduced motor unit action potential due to an inability to activate fast twitch fibers and failure to reach the stimulation threshold [28]. Therefore, slow-twitch fibers are additionally recruited to provide muscle contraction tensile force during fatigue. Because of the decreased ability of slow-twitch fibers to generate a contraction force compared to fast twitch fibers [29], a muscle must recruit a greater number of slow-twitch fibers instead of fast-twitch fibers to compensate and maintain the necessary constant force. Increased amplitude of EMG signals during a fatigue-associated exertion is due to a greater synchronization of action potentials and a larger population of recruited slower-twitch fibers. To quantify the amount of activity of the biceps brachii muscle, the IEMG value of each cycle was calculated for each of the MVC levels analyzed (Figs. 2(b), (e), (h) and (k)). Initially, IEMG values exhibited a linear increase; however, they increased abruptly in a non-linear fashion upon reaching a certain cycle number that was specific for each MVC level. It is noteworthy that these cycle numbers coincided with specific cycles in which the dumbbell curl exercise exceeded the desired cycle time (3 sec), as the subject could no longer follow the speed of the metronome (3 sec/cycle) due to accumulating muscle fatigue (see Figs. 2(c), (f) and (i)). The cycle numbers at point of transition from linear increase to non-linear increase of IEMG values were 70, 22 and 10 for 20 %, 35 % and 50 % of MVC, respectively. These cycle numbers were defined as the fatigue cycles for constant muscle contraction for each of the MVC levels evaluated in this study. The increase in cycle time due to increased muscle fatigue may have been due to alteration of cross-bridge kinetics, wherein slow-twitch fibers were more heavily recruited compared to fast-twitch fibers in fatiguing muscle and the slow-twitch fibers reached their peak tension and relaxed more slowly than fast twitch units [30]. However, in the case of 75 % MVC, the cycle time already exceeded the desired cycle time (3 sec) from the beginning of the measurements (Fig. 2(l)). This may have been because the 75 % MVC was too high of a load level for the subject to conduct the 3 sec dumbbell curl exercise. Therefore, 75 % MVC could be considered as an overload condition for the subjects. In the overload case, the IEMG value increased rapidly to over 200 % of initial IEMG value in only 5 cycles (Fig. 2(k)).

To investigate the relationship between IEMG values and muscle force, it is necessary to neglect the influence of cycle time because the IEMG value increased proportionally with cycle time (see Eq. (3)). To account for this issue, mean IEMG values were obtained by normalizing IEMG values using each cycle time (timecycle, j) using Eq. (4). As shown in Fig. 3, the mean IEMG values increased in an almost completely linear fashion as muscle fatigue accumulated, even though the influence of cycle time was neglected. In addition, it was found that that the initial mean IEMG value increased as the MVC level increased. The increasing slope of the mean IEMG due to fatigue decreased as the MVC level increased.



(a) (c) (e) (g)

(b) (d) (f) (h)

Fig. 4. Fast Fourier transform (FFT) analysis of the biceps brachii muscle at the initial and final cycles.

Furthermore, we found that all of the final values of the mean IEMG saturated at 250 μV, except for the case of 75 % MVC (overload condition), which was attributed to the longer cycle time (3 sec) required by subjects. Thus, the mean IEMG in the 75 % MVC case was already higher than 250 μV. Based on these data, we concluded that the mean IEMG value upon becoming fatigued was equal to ~250 μV during overload conditions.

In order to obtain information about fatigue, we performed Fast Fourier transform (FFT) on each windowed segment (Fig. 4).

The amplitude of the power spectrum increased as the MVC level increased. In addition, we found that the amplitude increased after the onset of muscle fatigue. These findings corresponded to the time domain analysis results (Fig. 2).

In particular, when the muscle was fully fatigued, the amplitude in the low frequency region increased (see Figs. 4 (b), (d), (f) and (h)). Several researchers have previously demonstrated a decrease in power density in the high frequency region (> 95 Hz) of EMG signals and an increase in the low frequency region (15-45 Hz) during fatiguing contractions [31-33].

Generally, this phenomenon is referred to as a “frequency shift” phenomenon. Furthermore, Lindstrom *et al.* demonstrated that the frequency shifts were almost entirely dependent on the propagation velocity of action potentials [34]. Such reduced propagation velocities have been linked to the production and accumulation of acid metabolites during muscle fatigue [35].

The median or mean frequency of the power density spectrum is usually used to characterize the frequency shift linked with fatigue. Lindstrom et al. demonstrated that the mean frequency of the power spectrum is proportional to propagation velocity [29]. In addition, Lindstrom and Petersen showed that decreases in mean frequency during isometric and isotonic contraction follow approximately exponential curves according to their respective time constants [36]. Likewise, the mean power frequency is a standard objective parameter used to trace muscle fatigue. Thus we examined the relationship between the initial MNF and fatigued MNF. Fig. 5 illustrates the dependence of the power spectrum on fatigue development. Similar to the results of previous studies [34-36], the MNF was reduced when the biceps muscle was fatigued for all MVC levels. In addition, we found that the decreasing rate of MNF due to muscle fatigue was nearly same for all load levels, which was approximately 40 % of the initial MNF as shown in Table 1. Therefore, it might be concluded that when a muscle is fatigued, the MNF value approaches 60 % of the initial MNF value regardless of load level (MVC level).

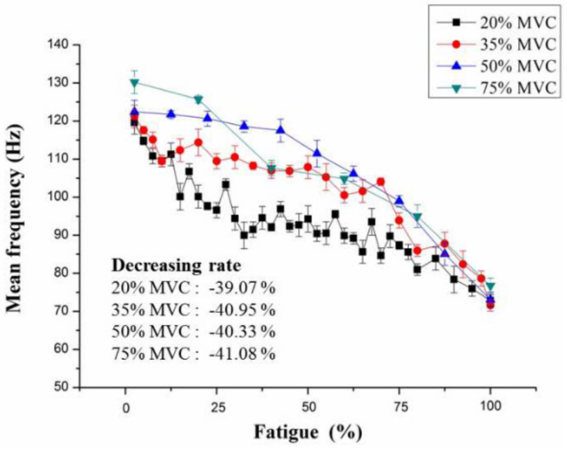


Fig. 5. Decrease in the mean frequency (MNF) of the biceps brachii muscle due to cyclic dynamic contractions.

By combining mean IEMG and MNF, we developed a global EMG index map to simultaneously trace both muscle fatigue and muscle force from EMG signals. Fig. 6 shows the proposed global EMG index map. As mentioned above, the

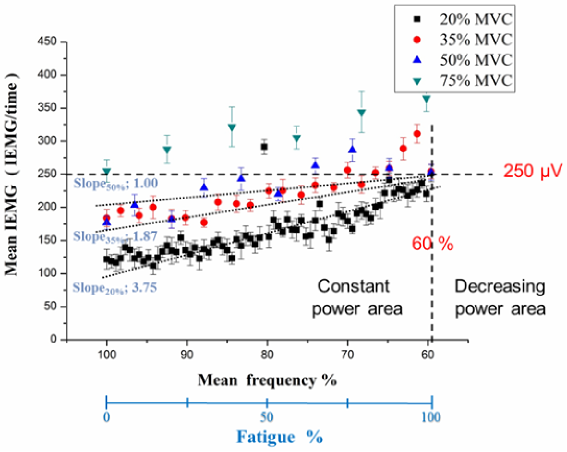


Fig. 6. Relationship between mean IEMG and MNF during fatigue accumulation of the biceps brachii muscle.

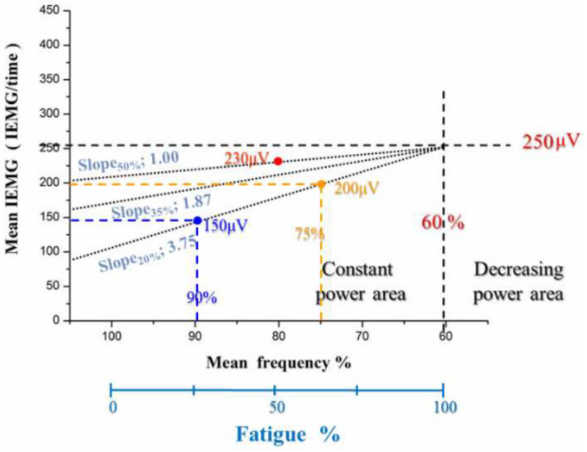


Fig. 7. Global EMG index map for evaluation of muscle fatigue and force.

fatigued muscle condition in this study was defined as the condition where the subject could no longer follow a predetermined metronome frequency (3 sec per cycle). Fig. 6 also shows that the bicep muscle was fully fatigued when the MNF decreased to 60 % of the initial MNF level, and the mean IEMG value saturated to 250 μV regardless of MVC level, except for the overload condition (75 % MVC). Meanwhile, we found that the initial value and increasing rate of the mean IEMG differed from each load level condition. Specifically, in the 75 % MVC case (overload condition), the mean IEMG value was already near 250 μV at the start of measurements.

Therefore, we concluded that the 75 % MVC case could not be considered using the same fatigue criteria in the global EMG index map.

Finally, as the MVC level increased, the initial value of the mean IEMG increased and the slope of the mean IEMG decreased. Based on these data, we concluded that that a combination of mean IEMG and MNF can be used to predict muscle fatigue and muscle force from EMG signals using the global EMG index map shown in Fig. 6 and the three following algorithms.

The degree of muscle fatigue can be defined by checking the MNF value. For example, if the measured MNF is less than 60 % of the initial MNF, the biceps muscle can be regarded as being fully fatigued (muscle power is decreased at this level) regardless of MVC level. If the measured MNF is 80 % of the initial MNF, the degree of muscle fatigue can be regarded as 50 % regardless of MVC level (see Fig. 6).

The mean value of IEMG and the slope of IEMG can provide the muscle force and fatigue level for constant MVC conditions. For example, if the IEMG value at a certain cycle is 230 μV and the slope of the IEMG increase at a given point is 1.00, the degree of fatigue degree and the force of the muscle can be regarded as 50 % and 50 % MVC, respectively (see Fig. 7). Likewise, if the IEMG value and the slope around the point are 250 μV and 1.87, respectively, the muscle can be regarded as being fully fatigued and the muscle load at that point can be predicted as 35 % MVC. However, the use of only IEMG value without MNF is limited to cases involving constant power exercise. In other words, if the MVC level is not constant, this algorithm cannot be used.

Finally, in the global EMG index map, the combination of the MNF and mean IEMG can provide information about muscle force and muscle fatigue simultaneously.

Specifically, the muscle force and degree of fatigue can be evaluated by finding the cross point between the mean IEMG value and MNF value from the EMG signal in the global EMG index map (Fig. 7). For example, if the mean IEMG and MNF values are 150 μV and 90 %, respectively, the muscle force and degree of fatigue degree can be predicted as 20 % MVC and 25 %, respectively. Similarly, if the mean IEMG and MNF values are 200 μV and 75 % of the initial MNF, the muscle force and degree of fatigue are 20 % MVC and 62.5 % (Fig. 7).

In order to verify our hypothesis regarding the above three algorithms and a global EMG index map for muscle fatigue/force evaluation, different MVC level dumbbell curl exercises were conducted together sequentially while each cycle time was fixed at 3 sec. First, 50 % MVC dumbbell curl exercise was conducted in 2 cycles followed by 5 dumbbell curl cycles at 35 % MVC. Finally, a 20 % MVC dumbbell curl was conducted for 10 cycles until the subject could no longer follow the 3 sec cycle. In these exercises, an interval of 3-4 sec was required for the subject to change dumbbells between exercises at different MVC levels. The mean IEMG and MNF values were calculated and plotted as shown in Fig. 8. It is noteworthy that the mean IEMG/MNF index map was consistent with the map constructed from the constant MVC level exercises shown in Fig. 6. It was also found that when the muscle was fully fatigued, the mean IEMG value was nearly saturated to 250 μV and the MNF value was decreased to 60 % of the initial MNF value, which was also similar to the results shown in Fig. 6. The 3-4 sec interval time between the different level MVC exercises mentioned above may have

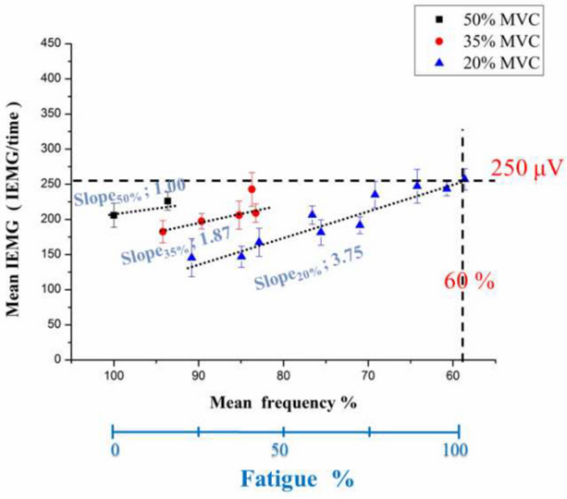


Fig. 8. Fatigue index for an exercise protocol mimicking sequential loading conditions (50 %, 35 % and 20 % MVC in order).

allowed fatigued muscles to recover as the MNF increased during subsequent exercises at different MVC levels. Specifically, one can compare the values between the last cycle's MNF value for 50 % MVC exercise and the initial cycle's MNF for 35 % MVC exercise as well as between the last cycle's MNF value for 35 % MVC exercise and the initial cycle's MNF for 20 % MVC exercise. From the global EMG index with the mean IEMG/MNF obtained from the various levels of MVC exercise, we concluded that the muscle fatigue/force evaluation algorithm in the global EMG index map may be adopted for different MVC isokinetic exercises as well as constant MVC isokinetic exercise. The proposed algorithm was verified for all five subjects who participated in this study.

A deeper investigation will be needed to fully validate the proposed algorithm and to expand the global EMG index map to different muscle power ranges (different cycle times). Research on this topic is in progress in our research group.

4. Conclusions

In the present study, several new algorithms for determining a global EMG index for muscle fatigue/force evaluation employing the mean IEMG and MNF were suggested and demonstrated. The effects of fatigue and load level on the EMG of biceps brachii were investigated in the time domain and the frequency domain, respectively. As a result, we found that the fatigue indices approached the fatigue point, which was 250 μV (mean IEMG) and 60 % MNF for all load levels. In addition, the muscle force and degree of fatigue could be evaluated by determining the cross points between the mean IEMG value and MNF value from the EMG signal in the global EMG index map. Furthermore, we showed that the global EMG index algorithm for simultaneous muscle fatigue/force evaluation could be adopted in different MVC isokinetic exercise as well as constant MVC isokinetic exercise. Taken together, these data indicated that the proposed global EMG index map could be used to simultaneously evaluate fatigue and force level. The results of this study should be helpful for diagnosing muscle fatigue. Likewise, the global index model suggested in this study is expected to improve worker safety and efficiency as well as to prevent musculoskeletal disorders associated with prolonged and chronic muscle fatigue.

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