Monitoring muscle fatigue following continuous load changes

Woojin Yoon

Department of Human Factors Engineering

Graduate School of UNIST

ULSAN NATIONAL INSTITUTE OF
SCIENCE AND TECHNOLOGY

Monitoring muscle fatigue following continuous load changes

A thesis/dissertation
submitted to the Graduate School of UNIST
in partial fulfillment of the
requirements for the degree of
Master of Science

Woojin Yoon

01. 06. 2020

Approved by

Shin

Advisor
Gwanseob Shin

Monitoring muscle fatigue following continuous load changes

Woojin Yoon

This certifies that the thesis/dissertation of Woojin Yoon is approved.

01. 06. 2020

Advisor: Gwanseob Shin

Gwanseob Shin

Sang Hoon Kang

Oh-Sang Kwon

ABSTRACT

Previous studies related to monitoring muscle fatigue during dynamic motion have focused on detecting the accumulation of muscle fatigue. However, it is necessary to detect both accumulation and recovery of muscle fatigue in dynamic muscle contraction while muscle load changes continuously. This study aims to investigate the development and recovery of muscle fatigue in dynamic muscle contraction conditions following continuous load changes. Twenty healthy males conducted repetitive elbow flexion and extension using 2kg and 1kg dumbbell, by turns. They performed the two tasks of different intensity (2kg intensity task, 1kg intensity task) alternately until they felt they could no longer achieve the required movement range or until they experienced unacceptable biceps muscle discomfort. Meanwhile, using EMG signal of biceps brachii muscle, fatigue detections were performed from both dynamic measurements during each dynamic muscle contraction task and isometric measurements during isometric muscle contraction right before and after each task. In each of 2kg and 1kg intensity tasks, pre, post and change value of EMG amplitude (AEMG) and center frequency were computed respectively. They were compared to check the validity of the muscle fatigue monitoring method using Wavelet transform with EMG signal from dynamic measurements. As a result, a decrease of center frequency in 2kg intensity tasks and an increase of center frequency in 1kg intensity tasks were detected. It shows that development and recovery of muscle fatigue were detected in 2kg and 1kg intensity tasks, respectively. Also, the tendency of change value of center frequency from dynamic measurements were corresponded with that from isometric measurements. It suggests that monitoring muscle fatigue in dynamic muscle contraction conditions using wavelet transform was valid to detect the development and recovery of muscle fatigue continuously. The result also shows the possibility of monitoring muscle fatigue in real-time in industry and it could propose a guideline in designing a human-robot interaction system based on monitoring user's muscle fatigue.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Research Background

1.1.1 Evaluation of muscle fatigue

Muscle fatigue is defined as a decline in the ability of a muscle to generate force. Prolonged exposure to muscle fatigue makes a person feel painful or even leads to injuries. Muscle fatigue depends on many peripheral and central factors. Peripheral fatigue is a decrease in force-generating capacity induced at or distal to the neuromuscular junction. On the other hand, central fatigue is a loss in neural drive or motor commands to the muscle, resulting in a reduction in force production or tension development.

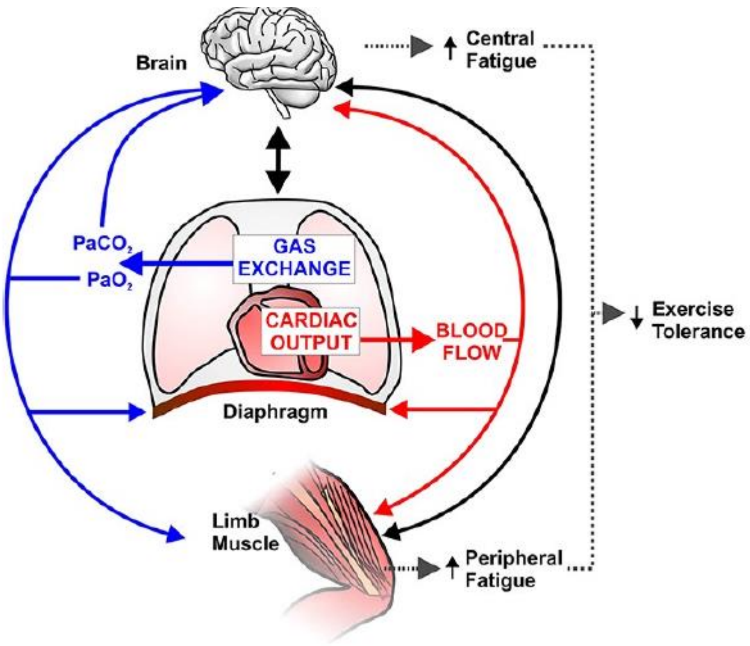

Figure 1. Types of muscle fatigue (Cifrek, 2009)

The onset of muscle fatigue is simply determined by measuring the time that an individual becomes unable to generate certain force consistently. Generally, the measurement is performed by keeping an isometric muscle contraction with a defined level of load. However, results obtained in this manner considerably rely on psychological factors such as motivation on the task (Enoka, 1995; Enoka & Duchateau, 2008).

Muscle fatigue can also be evaluated by physiological evidence. It has been suggested that muscle fatigue might be due to the decrease in propagation velocity of action potentials along the muscle fiber as a result of lactate accumulation within the working muscle (Broman, 1977; Komi & Tesch, 1979). Therefore, measuring lactate concentration in a muscle using blood samples is one of the methods to estimate muscle fatigue. However, taking blood samples and determining its lactate concentration is not possible to monitor the muscle fatigue in real-time.

Muscle fatigue can be assessed from the inducement of muscle stiffness. Resting tension develops when muscles get fatigued, and the greater resting tension results in greater muscle stiffness (Dresner et al., 2001). Therefore, it is assumed that muscle fatigue induces an increase in resting muscle stiffness. The resting muscle shear modulus is evaluated using shear wave ultrasound elastography as a muscle stiffness index (Dieterich et al., 2017; Eby et al., 2015) and has been used to evaluate the degree of peripheral fatigue before and after a fatiguing task (Akagi, Fukui, Kubota, Nakamura, & Ema, 2017). A previous study indicated that the combination of evaluating muscle stiffness and traditional methods, such as surface electromyography (EMG) and evoked torque, may be helpful for more accurately investigating muscle fatigue (Akagi et al., 2017).

Traditionally, measuring the myoelectric activity of particular muscles with surface EMG has been proved to give reliable information on muscle fatigue detection and used by many researchers to extract features of muscle fatigue. Fatiguing of muscle changes biochemical and physiological muscle property and it is represented in myoelectric signals recorded on the surface of the skin above the muscle concerned (De Luca, 1984).

Assessment of muscle fatigue based on EMG has limitations that the way is valid for muscles which are located directly below the skin. Also, the signals from surrounding muscles can interfere with the result (Farina, Fattorini, Felici, & Filligoi, 2002). However, the method of EMG has been generally used to assess muscle fatigue because of its principal advantages of non-invasiveness, applicability in situ and ability to detect fatigue of a particular muscle (Cifrek, Medved, Tonkovic, & Ostojic, 2009).

1.1.2 Muscle fatigue assessment based on EMG

Fatigue assessment in isometric muscle contraction

It has been well known that, under well-controlled conditions, muscle fatigue during submaximal isometric muscle contractions is accompanied by increases in EMG amplitude and decreases in center frequency. Cobb and Forbes (1923); Lippold, Redfearn, and VuČO (1960) noted that the amplitude of EMG signal increases as one of the indicators of muscle fatigue during an isometric contraction. It has been investigated that increases in EMG signal amplitude which is generated from muscle fatigue may be attributable to the recruitment of new motor units (Farina, Merletti, & Disselhorst-Klug, 2004). Others proposed that the synchronization of motor unit firing is increased from muscle fatigue and subsequently increase EMG amplitude (Farina, Fosci, & Merletti, 2002). However, the increase of EMG amplitude is rarely used as an absolute indicator of muscle fatigue because it considerably depends on external factors such as muscle load or posture. Therefore, generally, muscle fatigue is assessed by combination with spectral analysis (Joint Analysis of EMG Spectrum and Amplitude, JASA).

In a frequency domain, the shift of the EMG signal spectrum toward lower frequencies can be detected during sustained muscle contraction as a dominant indicator of muscle fatigue development. Frequency analysis of myoelectric signals to evaluate muscle fatigue was provided by Petrofsky and Lind (1980), who observed the shift of EMG signal spectrum to lower frequencies. Many researchers reported similar observations in various muscles with different explanations (De Luca, 1984). It has been reported that increased concentration of the lactates is responsible for fatigue by changes in intracellular pH. As a result, muscle fiber conduction velocity (CV) decreases. Brody, Pollock, Roy, De Luca, and Celli (1991) reported that the decrease of muscle fiber CV is determined from the decrease of intracellular pH. As a consequence, the signal power spectrum shifts toward lower frequencies, and the EMG signal amplitude is increased. Besides the decrease of fiber CV, the remaining activity of the slow motor units which is accompanied by fatiguing and switching off fast ones was assumed as the cause of the shift of the EMG power spectrum.

Previous studies have introduced several fatigue indexes processed from EMG signals on the frequency domain. In the earliest investigations, Fourier transform was the most often used method for estimating the spectrum of the EMG signal. Kwatny, Thomas, and Kwatny (1970) applied the signal processing method to explore properties of the power spectrum density of a surface myoelectric signal recorded during a static fatiguing task. They introduced the mean frequency of the spectrum to determine differences before and after fatigued. Many studies have noted that the frequency-based EMG variables are less dependent than amplitude on the instantaneous force level of muscle and are, therefore, more sensitive to fatigue-related changes. (frequency shift physiological evidence)

Fatigue assessment in dynamic muscle contraction

Although fatigue is normally resulted from dynamic movement and exercise, the majority of researches in the past was quantified muscle fatigue in static muscle contractions situations. Isometric contractions have served as a standard for EMG-based fatigue quantification, but recent evidence suggests that fatigue may also cause changes in EMG signals measured during dynamic contractions. In a dynamic muscle contraction situation, the EMG signal from muscle can no longer be considered as steady state.

Therefore, The way to assess changes in the frequency content of EMG signals which is resulted from muscle fatigue has been investigated over the last decade. Therefore, various time-frequency signal processing methods such as short-time Fourier transform, Choi-Williams distribution, and Wavelet transform have been suggested to find suitable spectral estimation techniques. S. Karlsson, Yu, and Akay (2000) reported that continuous wavelet transform provided best accuracy in analyzing EMG signals during dynamic contractions among short-time Fourier transform, the Wigner–Ville distribution, the Choi–Williams distribution.

Wavelet Transform

A number of studies have mentioned that wavelet transform has a good performance in time-frequency localization of EMG signal for fatigue detection (S. Karlsson et al., 2000). The basic idea of wavelet analysis is expressing a signal as a linear combination of a particular set of functions obtained by shifting and dilating one single function called a mother wavelet (Hostens, Seghers, Spaepen, & Ramon, 2004). Considering Wavelets as building blocks for general functions, it is possible to express any general function as an infinite series of Wavelets. Several different mother wavelets have been studied. Based on the mother wavelet, the signal is decomposed to a set of coefficients called wavelet coefficients and reconstructed as a linear combination of the wavelet functions weighted by the wavelet coefficients.

In contrary to the short-time Fourier transform (STFT) which has been commonly used for regularly segmented signals to add time domain to frequency domain, a wavelet analysis varies the time-frequency aspect ratio. It produces good frequency localization at low frequencies (long time windows), and good time localization at high frequencies (short time windows (Hostens et al., 2004)). Figure 2 illustrates the difference between the short-time Fourier transform and the Wavelet transform.

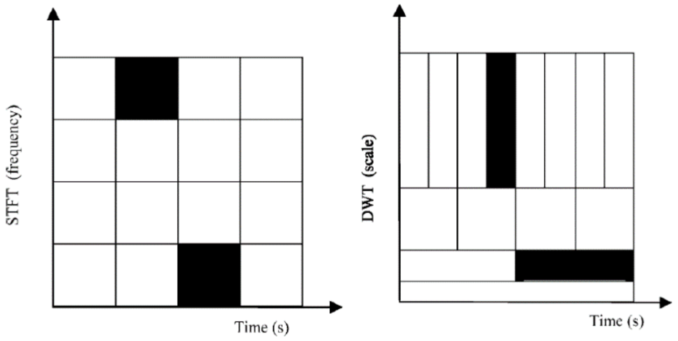

Figure 2. The tiling of the time-frequency plane in the case of STFT (left) and the tiling of the time-scale plane in the case of DWT (right) (Hostens, 2004)

There are two types of wavelet: the continuous (CWT) and the discrete wavelet transform (DWT). Unlike the discrete wavelet transform, the CWT can operate at every scale. Therefore, in the case of EMG signals, the CWT will provide the most information and most detail. Given the input signal x(t), the CWT is defined as:

$$CWT_x(s,\tau) = \int x(t)\varphi^*_{s,\tau}(t)dt \tag{1}$$

where s is the scale parameter, t is the translation parameter (time shifting). The basic function $\varphi_{s,\tau}(t)$ is obtained by scaling the mother wavelet $\varphi(t)$ at time τ and scale s. The power density function which called Scalogram SCAL of CWT is estimated with:

$$SCAL(\tau,s) = \mid CWT_x(s,\tau) \mid^2 \tag{2}$$

An example of the Scalogram as calculated for dynamic biceps contractions is shown in Figure 3. Following the process, wavelets can analyze waveforms in very short duration so that changes in timing and frequency content can be evaluated simultaneously. Also, Wavelet transforms are effective in removing undesired artifacts from data, such as those caused by subject movement or other noise sources.

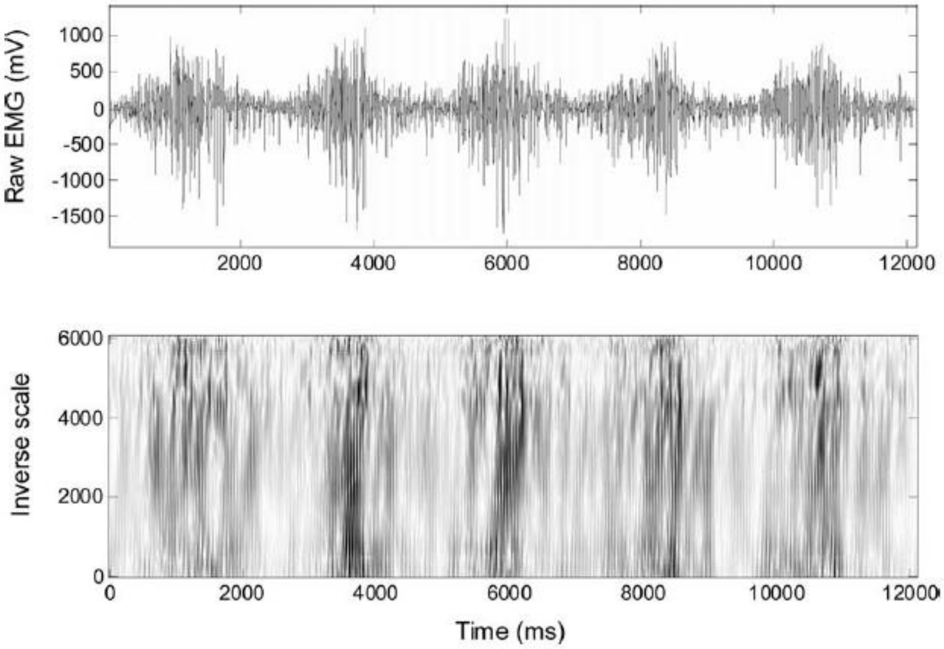

Figure 3. Scalogram for several dynamic biceps brachii contractions. The y-axis of the scalogram is in inverse scales. (Hostens, 2004)

Many previous studies proved the validity of CWT to detect the development of muscle fatigue in various muscles and motions such as elbow flexion (Hostens et al., 2004) or running (Koenig et al., 2018). However, the application of the method of detecting recovery of muscle fatigue has rarely been investigated. Kuorinka (1988) reported that the increase of mean frequency occurred when upper limb muscle got recovered after a fatigue experiment. Also, Larivière, Arsenault, Gravel, Gagnon, and Loisel (2002) detected recover of back muscle fatigue using EMG signals and checked its reliability. Chowdhury, Nimbarte, Jaridi, and Creese (2013) also showed recovery of shoulder muscle fatigue in a 5min recovery session between repetitive fatiguing arm exertion sessions using the EMG signal processed by DWT. However, these were limited to the identification of recovery of muscle fatigue during the resting conditions. Investigation about change in muscle fatigue values after lowering muscle load during continuous dynamic muscle contraction, without stopping the repetitive motion has not been performed yet.

1.1.3 Application of EMG based muscle fatigue assessment

EMG signals have a wide range of applications, such as in rehabilitation and assistive technologies, ergonomics, clinical diagnosis, and sport science (Bi, Feleke, & Guan, 2019). Mechanized work in an industry usually requires repetitive physical work which accompanies neuromuscular fatigue on muscles, and the muscle fatigue results in the occurrence of musculoskeletal disorder and, eventually, a decrease in productivity of the system. To solve the problem, recent trend in industrial field is to investigate assistive devices which rely on the EMG signal of workers to generate the desired assistive force/torque and improve workers' health and productivity (Bai, Lubecki, Chew, & Teo, 2012; Peternel, Fang, Tsagarakis, & Ajoudani, 2019). The system that humans and robots work together is called Human-Robot collaboration (HRC) and it has advantages in using human's superior flexibility/adaptability and retaining the jobs for the human workers. One of the key problems of HRC is to make humans and robots aware of intentions of each other, and intelligently collaborate to achieve manufacturing objectives. For one instance, muscle fatigue evaluated from EMG signals of workers can provide evidence of their condition and control assistance robot. Thus, the assessment of muscle fatigue plays an important role in such devices. The assessment of muscle fatigue in dynamic muscle contraction conditions is especially important because performing traditional isometric fatigue tests requires interruption of workers and it generates a loss of productivity.

Several researchers investigated methods to evaluate muscle fatigue related to Human-Robot collaboration and confirmed its validity (Bai et al., 2012; Hamaya, Matsubara, Noda, Teramae, & Morimoto, 2017; Peternel et al., 2019). However, there are no, or few investigations about the change of muscle fatigue after the intervention of an assistance robot lowering muscle load. The detection of muscle fatigue before robot intervention is also important to control follow-up assistance appropriately. Also, the research about the response of muscle fatigue following a continuous change of muscle load can be extended to the prediction of time the workers could sustain and continue the repetitive manual job in Human-Robot collaboration system to facilitate robot intervention.

1.2 Research Objectives

Therefore, there is a clear need for research related to the detection of muscle fatigue in dynamic muscle contraction conditions accompanying the continuous change of muscle load. There were two objectives in this study. The first was to evaluate biceps brachii muscle fatigue while changing the intensity of the dynamic muscle contraction continuously. The second was to compare two fatigue evaluation methods each of which were based on Fourier transform in isometric muscle contraction situation and Continuous wavelet transform in dynamic muscle contraction situation.

1.3 Research hypotheses

First, it was hypothesized that the development of biceps brachii muscle fatigue would be detected during conducting elbow flexion/extension using 2kg dumbbell and the fatigue would be detected to be recovered during the following elbow flexion/extension using 1kg dumbbell.

Second, the same tendency of development and recovery of muscle fatigue between isometric measurement and dynamic measurement was expected to be observed.

2. METHOD

2.1 Participants

Twenty young healthy males volunteered to participate in the study. Participants who had discomfort in conducting elbow flexion and extension movement with load were excluded, and all participants do light exercise more than once a week. Five of the participants were left-handed, and the rest were right-handed. There was no skin allergic reaction to alcohol for all participants that were used for utilizing EMG sensors. Informed consent approved by the institutional review board was provided prior to conduct the experiment. Table 1 shows the participant information.

Table 1. Participant information mean (standard deviation)

The number of participants	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
20	22.40 (1.77)	175.20 (4.95)	74.25 (9.15)	22.16 (2.54)

2.2 Instruments

2.2.1 Electromyography (EMG) measurement system

10-channel digital EMG system (FlexComp Infiniti System, Thought Technology Ltd., Canada) was used to collect the EMG signal of biceps brachii muscle while conducting the task. The non-invasive Ag-AgCl triode surface EMG sensor (MyoScan-z) was able to detect EMG signals from 0 - 2000µV within a frequency range from 20 to 500Hz. EMG data were collected at 2048Hz.

Figure 4. FlexsComp system and EMG sensor (myoscan-z)

2.2.2. Motion capture system

A 3D motion capture system (OptiTrack V120: Trio, NaturalPoint, Inc., OR) was used to track arm movement. Three cameras in a tracking bar detected infrared light and allowed obtaining spatial information of marker positions at a sampling frequency of 120 Hz. The tracking bar was located 2 m from the lateral side of the dominant arm and at the height of the elbow of each participant.

Three axes were defined as follows: anterior-posterior axis as X-axis, superior-inferior axis as Y-axis, and medial-lateral axis as Z-axis. Three axes location and rotation data for each rigid body were recorded. Data acquisition and filtering were performed with the software Motive (NaturalPonint Inc., Corvallis, OR).

Figure 5. 3D motion capture system (Optitrack V120: Trio)

2.3 Experimental protocol

Session I: Preparation

There are three sessions in this laboratory experiment (Figure 8). Session I was the preparation stage. An experimenter collected participants' age and measured their height and weight.

Prior to the attaching EMG electrodes, dead cells were removed by cleaning each participant's skin with ethyl alcohol (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). An Ag-AgCl triode surface EMG sensor (Flexcomp, Thought Technology, Canada) was attached to the most prominent bulge of the biceps brachii muscle belly of the participant's dominant side (Hermens et al., 2000). The muscle was chosen to assess the physical demands of repetitive elbow flexion and extension.

Three reflective markers were located to the center of the radius and lateral side of the greater tuberosity to construct rigid bodies of the forearm and upper arm, respectively. The reflective markers were tracked by a motion capture system to quantify the elbow flexion-extension movement.

Session II: Maximum Voluntary Contraction (MVC) measurement and Practicing

Maximum Voluntary Contraction (MVC) EMG of the biceps brachii muscles was recorded to normalize EMG data during tasks. The participant seated on a chair with the upper arm pointing downward and the forearm pointing forward. To obtain MVC, they exerted the maximum elbow flexion against an experimenter pushing his forearm downward in a seated posture. To compute the mean MVC EMG amplitude of the biceps brachii muscle, the middle 1s window from the EMG signal during MVC was selected and averaged. One-minute rest was provided after each exertion for recovery.

Also, a reference upper limb posture was defined in full elbow extension posture with the upper limb vertical to the ground. The sagittal plane angles of the upper arm and forearm rigid bodies in the reference posture were defined as 180° orientations. (Figure 6) Prior to the main task, time for training and practicing were given sufficiently to make the participants reduce the learning effect and perform warm-up.

Figure 6. Reference posture (elbow flexion angle = 180°)

Session III: Main experiment and Data collection

After sufficient rest, until the participants didn't feel any fatigue on their upper limb, they conducted the main task. The main experiment was conducted while on a chair in a stabilized seated posture. They were tightened to the chair to minimize the use of other body parts (Figure 7). The main experiment consists of two intensities of dynamic contraction tasks.

Two intensities of dynamic contraction tasks included: '2kg intensity task' and '1kg intensity task' where participants performed repetitive elbow flexion and extension of the dominant arm with a given weight of dumbbell for 2 minutes. (Figure 7) In each intensity of dynamic contraction tasks, the weight of the dumbbell was 1kg and 2kg, respectively (Figure 9). Right after the experimenter gave selected dumbbell to the participants, they were asked to start repetitive elbow flexion and extension with verbal signal “start” from the experimenter. The motion was ranged from full elbow extension to full elbow flexion. The pace of the cycle of elbow flexion and extension was restricted to be repeated every 3 seconds (2/4, 40 bpm). To indicate the start points of each elbow flexion and extension, sound from the metronome was provided. Participants were encouraged to continue regular dynamic contraction tasks until they felt they could no longer perform the required movement range or they felt unacceptable biceps brachii muscle discomfort. The weight of dumbbells was chosen after several pilot tests considering participants' safety and repeatability that an adult male could run at least four sets of 2kg and 1kg intensity tasks with a weight in the hand. However, the number of sets that each participant could perform was different. At the point where a participant proceeded the next 2kg intensity task following 1kg intensity tasks, it was considered the participants proceeded another set of 2kg and 1kg intensity tasks.

During the entire main experiment, muscle fatigue measurement was performed. While participants performed each task, “dynamic measurements” were performed to evaluate the progress of muscle fatigue. Also, right before and after each task, “Isometric measurements” were performed to evaluate the change of muscle fatigue during each task. For isometric measurements, the experimenter gave 6kg load to participants with giving verbal signal “start”. Then, participants conducted isometric muscle contraction of biceps brachii by holding the load on their dominant hand for 6 seconds with the posture that forearm parallel to the ground (elbow angle of 90°) (Figure 7, left). The weight of the load that participants needed to hold in isometric measurements was selected with 30~40% of the average maximum voluntary isometric contraction torque of the elbow joint. Participants’ biceps brachii muscle was activated as 38.14% MVC which was targeted in this study.

Figure 7. Scenes of isometric measurements (left) and dynamic measurements (right)

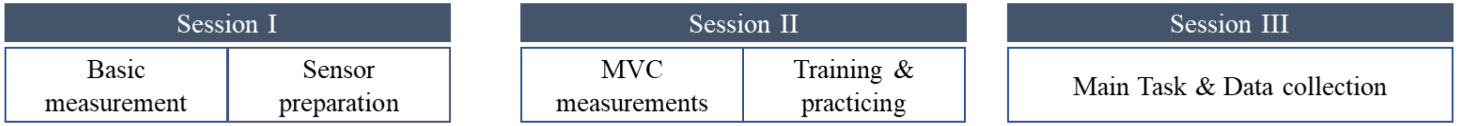

Figure 8. Overall protocol of the experiment

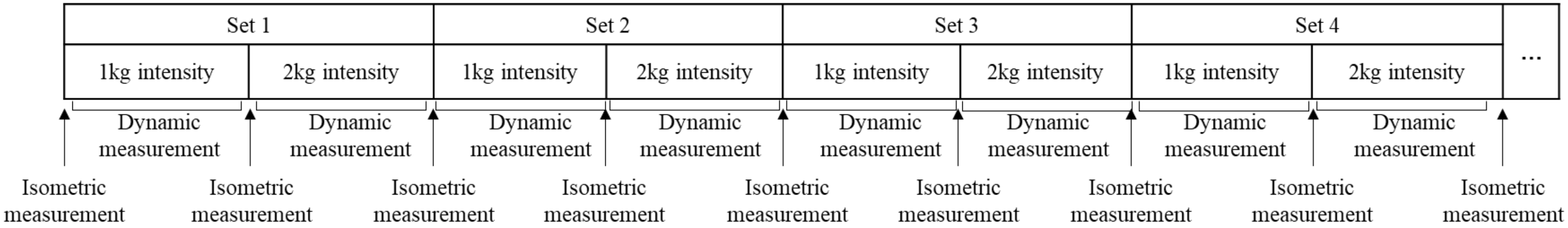

Figure 9. Protocol of main task

2.4 Data processing and analysis

2.4.1 Movement tracking

Acquisition and filtering of upper limb kinematic data were conducted with Motive (NaturalPoint Inc., Corvallis, OR). After collecting the movement data of the upper limb, using 'Fill gaps' function. missed data points were reconstructed. It calculated the missing markers trajectory with interpolation methods. Unwanted noise was also filtered out using the 'Smooth function' with a cut-off frequency of 6 Hz.

Kinematic data of forearm and upper arm in the sagittal plane was used to confirm whether participants performed regular elbow flexion and extension. Elbow joint angle was defined as the subtraction of the forearm flexion angle from the upper arm flexion angle. The mean value of peak elbow flexion (-) and extension (+) velocity was calculated from all the 40 cycles in each task.

2.4.2 Muscle fatigue evaluation

Muscle fatigue evaluation was conducted based on the EMG signal of biceps brachii muscle from both isometric and dynamic measurement. Raw EMG signal was recorded at 2048Hz. The raw EMG signal was bandpass filtered (10-500Hz) and 2nd order low-pass Butterworth filter with a cut-off frequency of 6 Hz was used to smooth the data. To remove any interference from electrical devices, a notch filter with 60Hz was used to. These processes were conducted through MATLAB 2019a (The MathWorks Inc., Natick, MA).

The processed EMG data were analyzed to evaluate fatigue values by calculating central frequency and amplitude of EMG signal from each isometric and dynamic measurement. From EMG signal during isometric measurement, pre, post and change (post-pre) value of EMG amplitude (AEMG) and median frequency (MDF) were obtained. From EMG signal during dynamic measurement, pre, post and change (post-pre) value of EMG amplitude (AEMG) and instantaneous mean frequency (IMNF) were obtained.

To obtain fatigue value with the amplitude of EMG signal from each measurement, the processed EMG data were normalized to the maximum EMG amplitude obtained during a maximum voluntary contraction (MVC). In isometric measurement, using middle 4s data among each 6s measurement, mean amplitude values of the normalized EMG data (AEMG) were computed in pre and post-stage in each task. By subtracting AEMG in the pre-stage from that in the post-stage, change in AEMG value was computed. In the case of normalized EMG data collected during dynamic measurements, the AEMG data were calculated for each entire 2-minute task.

Center frequency was calculated differently in the isometric measurement and the dynamic measurement. Because collected EMG signals from the isometric measurement were stational, median frequency (MDF) was calculated from middle 4s as the central frequency using Fourier Transform. Pre, Post, and Change (Post - Pre) value of MDF during each intensity of tasks were computed to evaluate the change of fatigue value. When analyzing EMG signals from the dynamic measurements, the center frequency was calculated using Continuous wavelet transform. In each of 2 min of 2kg and 1kg intensity task, Instantaneous mean frequency (IMNF) was computed using Eq. (3):

$$\mathrm{IMNF} = \frac{\int_{ls}^{hs} \mathrm{s} \times \mathrm{SCAL(s)} ds}{\int_{ls}^{hs} \mathrm{SCAL(s)} ds} \tag{3}$$

With ls the lowest scale and hs the highest scale of interest.

Once the time histories of AEMG and IMNF over time while conducting each task were determined, average values were taken from each 40 flexion and extension cycles (3s/cycle). Using averaged AEMG and IMNF values from each task, a second-order polynomial regression analysis was performed to develop models for predicting the progress of the magnitude of AEMG and IMNF with cycles. These polynomial equations were used to estimate the change in AEMG and IMNF overtime during each task. The first and final values predicted by each model at the first and the last cycle (40th cycle) of each task were used to represent the fatigue values of the pre and post-stage of each task. The change in AEMG and IMNF was calculated by subtracting the estimated final value from the first value (40th value – 1st value) (Figure 10).

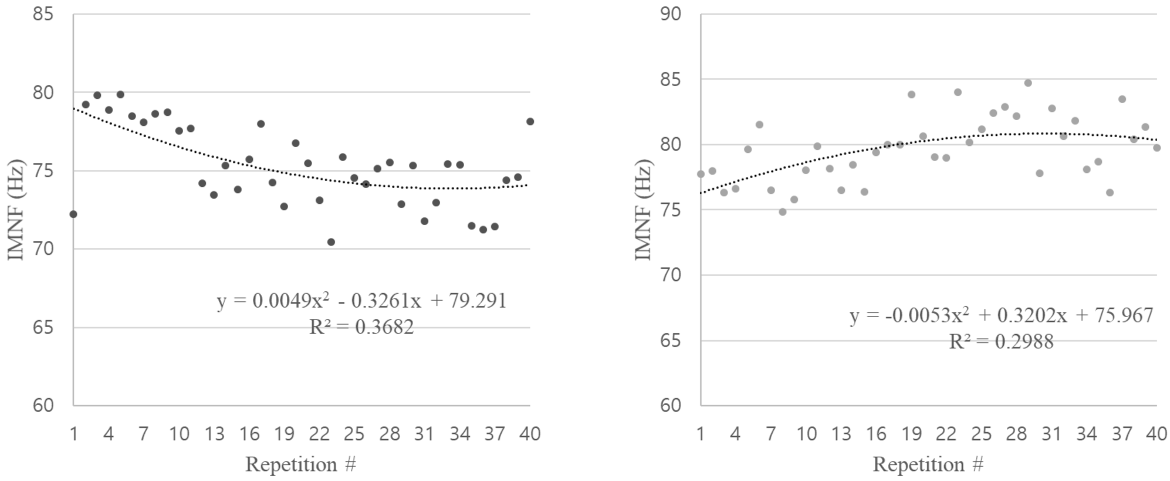

Figure 10. Example polynomial regression model of IMNF during one set of 2kg intensity task (left) and 1kg intensity task (right)

2.5 Statistical analysis

Using mean peak elbow flexion and extension velocity during the tasks, it was evaluated whether participants conducted regular elbow flexion and extension motion between 2kg intensity tasks and 1kg intensity tasks. The peak elbow flexion and extension velocity were averaged out among the cycles and the sets of each task. One-way repeated-measures ANOVA was performed to compare elbow joint motion between 2kg and 1kg intensity task. The participants variable was regarded as a random factor.

To verify the first hypothesis and check the significance of the development and recovery of the biceps brachii muscle fatigue during each 2kg and 1kg intensity task, pre and post values of AEMG and center frequency (MDF and IMNF) were compared in each intensity of tasks as dependent variables from EMG signals. All dependent variables were averaged out over the performed sets of each intensity of task in each subject. To compare pre and post values of AEMG and center frequency from isometric measurement and dynamic measurement, one-way repeated-measures ANOVA was used in each intensity of the task. The participants variable was regarded as a random factor.

To verify the second hypothesis, it was checked whether both dynamic and static fatigue measurement methods could detect the development and recovery of muscle fatigue significantly and whether the change tendency would be the same or not. Therefore, as dependent variables from EMG signals, the change values of AEMG and center frequency (MDF and IMNF) from both dynamic and static measurements were calculated and were compared between the two intensity levels of tasks (2kg intensity vs 1kg intensity). Also, the accordances of the tendency of the change values were quantified by calculating accordance rates of increase and decrease of fatigue values between the two measurement methods. In addition, correlation coefficients between the two measurement methods were calculated with the change values during both 2kg and 1kg intensity. Minitab 18 (Minitab Inc., State college, PA, USA) was used to conduct all statistical analyses.

3. RESULTS

3.1 Movement tracking

There was no significant effect of intensity of task on mean peak velocity of flexion (F(1,19)=2.18, p=0.156) and extension velocity (F(1,19)=0.58, p=0.46) (Figure 11, Table 2).

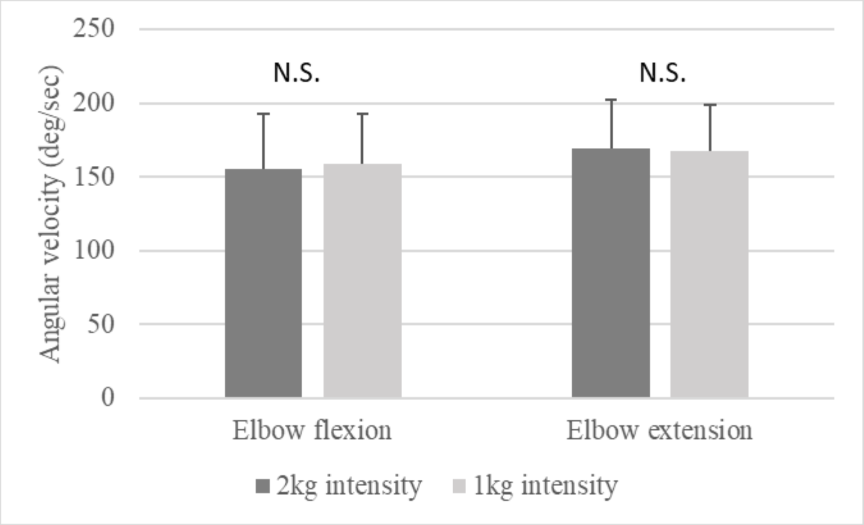

Figure11. Mean peak angular velocity while conducting tasks

Table 2. Mean peak angular velocity while conducting tasks. Mean (standard deviation)

Peak joint angular velocity (Deg/s)	Intensity of tasks			
	2kg intensity	1kg intensity	F	p
Elbow flexion	155.15 (37.97)	169.23 (33.00)	2.18	0.156
Elbow extension	159.23 (33.54)	167.16 (31.88)	0.58	0.46

3.2 Muscle fatigue detection

3.2.1 Comparison between pre-stage and post-stage of tasks

In fatigue evaluation from isometric measurement, a significant decrease of MDF from pre-stage of tasks (98.89 Hz) to post-stage of tasks (93.65 Hz) was found in the 2kg intensity tasks (F(1,19)=30.94, p=<.001). A significant increase from pre MDF (93.65 Hz) to post MDF (97.09 Hz) was found in 1kg intensity tasks (F(1,19)=27.98, p=<.001). AEMG data evaluated from isometric measurement didn’t have a significant difference between pre (50.82 %MVC) and post AEMG (51.38 %MVC) while conducting the 2kg intensity tasks (F(1,19)=0.47, p=0.501). Pre AEMG (53.34 %MVC) significantly increased to post AEMG (56.29 MVC) while conducting 1kg intensity tasks (F(1,19)=8.4, p<.01) (Table 3).

Fatigue evaluation from dynamic measurement showed that, during the 2kg intensity tasks, there was a significant decrease in IMNF (pre: 86.61 Hz, post 83.58Hz) (F(1,19)=39.34, p=<.001). A significant increase of IMNF (pre: 81.09 Hz, post: 86.19 Hz) was also found in the measurement during the 1kg intensity tasks (F(1,19)=143.69, p=<.001). AEMG evaluated from dynamic contraction was found to be increased (pre: 27.41 %MVC, post: 32.21 %MVC) in the 2kg intensity tasks (F=27.88, p=<.001) but had no significant difference between pre AEMG (19.76 %MVC) and post AEMG (20.17 %MVC) in the 1kg intensity tasks (F=0.53, p=0.474) (Table3).

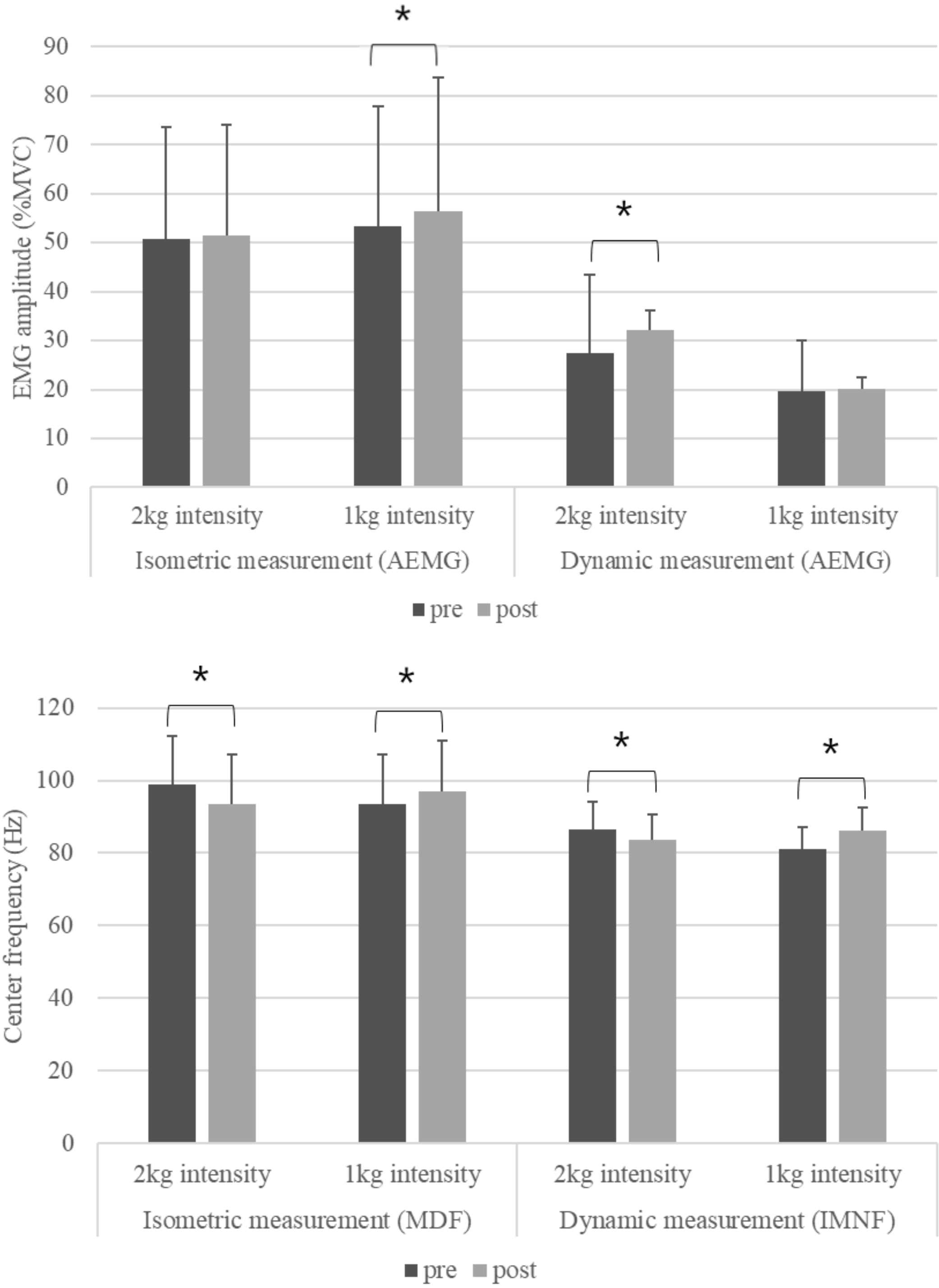

Figure 12. Pre and post values of AEMG (top) and center frequency (bottom) in each intensity of task

Table 3 Pre and post values of each dependent variables and ANOVA results. Mean (standard deviation)

		Center frequency (Hz)		F	p-value	Amplitude (%MVC)		F	p-value
		pre MDF	post MDF			pre AEMG	post AEMG		
Isometric measurements	2kg intensity	98.9 (13.4)	93.7 (13.6)	30.94	<0.001	50.8 (22.86)	51.38 (22.7)	0.47	0.501
	1kg intensity	93.7 (13.6)	97.1 (14.0)	27.98	<0.001	53.34 (24.5)	56.29 (27.3)	8.4	<0.01
		pre IMNF	post IMNF			pre AEMG	post AEMG		
Dynamic measurements	2kg intensity	86.6 (7.6)	83.6 (7.2)	39.34	<0.001	27.41 (13.2)	32.21 (16.1)	27.88	<0.001
	1kg intensity	81.1 (6.1)	86.2 (6.3)	143.69	<0.001	19.76 (10.4)	20.17 (10.2)	0.53	0.474

3.2.2 Effect of intensity of fatigue tasks

In fatigue evaluation from both isometric and dynamic measurements, a significant effect of intensity of task was found on change values of AEMG and center frequency. Isometric measurement shows that MDF change while conducting 1kg intensity tasks (+0.56 Hz) and 2kg intensity tasks (-5.24 Hz) were significantly different (F(1,19)=32.12, p=<.001). In the case of change value of AEMG from isometric measurement, a significant difference between 1kg intensity task (-2.95 %MVC) and 2kg intensity task (+0.56 %MVC) was found (F(1,19)=3.89, p=<.01). (Table 4)

There was a significant effect of intensity of task on change value of IMNF (2kg intensity: -3.03 Hz, 1kg intensity: +5.10 Hz) collected from dynamic measurement (F(1,19)=128.72, p=<.001). AEMG change was found to be increased by 27.41 %MVC during 2kg intensity tasks and decreased 19.76 %MVC during 1kg intensity tasks. The difference of AEMG change between two intensity of task was statistically significant (F(1,19)=13.29, p=<.01). (Table 4)

Table 4. Change values of each dependent variables and ANOVA results. Mean (standard deviation)

	Isometric measurements		F	p-value
	2kg intensity	1kg intensity		
MDF change (Hz)	-5.24 (4.10)	3.44 (2.83)	32.12	<0.001
AEMG change (%MVC)	0.56 (3.58)	2.95 (4.44)	3.89	<0.01
	Dynamic measurements		**F**	**p-value**
	2kg intensity	1kg intensity		
IMNF change (Hz)	-3.03 (2.11)	5.10 (1.85)	128.72	<0.001
AEMG change (%MVC)	27.41 (13.23)	19.76 (10.35)	13.29	<0.01

3.2.3 Comparison of fatigue evaluation from isometric and dynamic measurements

Table 5 shows that the accordance rates of increase and decrease of center frequency between dynamic and isometric measurement methods were ranged from 60~100% (average: 78.2%, standard deviation: 14.1%). Also, the accordance rates of increase and decrease of AEMG between dynamic and isometric measurement methods were ranged from 50~83.3% % (average: 61.8%, standard deviation: 11.7%). (Table 6)

A strong positive correlation (r > .70) for the biceps brachii muscle was found between MPF change from isomeric measurements and IMNF change from dynamic measurements. A very weak correlation (r=-.11) was found between AEMG change from isometric measurements and dynamic measurements. (Figure 13)

Table 5. Raw change values of center frequency from isometric measurements (MDF) and dynamic measurements (IMNF) with the accordance rates between two measurement methods. The unit of change values was Hz and that of accordance rates was %.

subj #	Variable	Set1		Set2		Set3		Set4		Set5		Set6		Set7		Set8		Set9		Accordance rate
		2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	
1	Iso	-17	11	-6	8	-13	4	-4	-4											87.5
	Dyn	-5	4	-2	3	-3	4	-7	1											
2	Iso	-5	12	-17	14	-18	6	-15	13											100
	Dyn	-1	4	-1	6	-3	4	-4	10											
3	Iso	12	6	0	-4	8	-11	-4	4	3	1	-8	11							58.3
	Dyn	-5	3	-4	4	-2	7	-6	4	-6	8	-4	4							
4	Iso	8	5	-7	0	1	5	-9	1	-2	-3	-3	7							58.3
	Dyn	-3	3	0	6	1	5	0	4	2	4	1	6							
5	Iso	-4	1	-2	1	-3	4	-5	1	-2	2	-5	4							100
	Dyn	-6	3	-4	3	-3	6	-3	6	-2	4	-4	3							
6	Iso	-11	5	-18	21	-10	7	-8	7	-3	-4	-1	11	-8	3					78.6
	Dyn	-7	4	-1	3	-3	3	0	8	1	8	-5	1	-1	4					
7	Iso	-12	5	-7	5	1	-1	-1	2	-4	0									80
	Dyn	-4	8	-5	7	-4	7	-3	5	-6	4									
8	Iso	-10	8	-10	8	-6	5	-7	1	1	2									80
	Dyn	-7	3	-5	3	-6	1	-3	1	-3	-1									
9	Iso	2	-3	-10	6	-16	8	-10	3	-10	9									80
	Dyn	-2	10	-2	7	-2	7	-2	5	-1	6									
10	Iso	-7	3	-3	2	-6	3	-8	7	-2	-6	3	-7	9	-12					64.3
	Dyn	-3	4	-3	7	-5	7	-4	5	-7	7	-7	7	-5	8					
11	Iso	-7	2	1	-2	-4	4	2	5	-4	-2									60
	Dyn	0	8	0	7	-1	5	3	3	-1	4									
12	Iso	0	8	-9	4	-4	3	-4	5	-9	7	-11	2							91.7
	Dyn	2	8	-1	8	-2	4	-1	8	-1	5	-3	5							
13	Iso	0	-1	-6	7	-3	-1	-2	2	-2	2	-3	-4							66.7

	Dyn	-5	2	-4	-1	-2	1	0	3	-2	2	0	3							
14	Iso	-5	4	1	-1	-1	4	0	3	5	2	-1	1	3	-7	9	1	-2	-2	61.1
	Dyn	2	2	3	3	0	3	0	4	-2	5	-1	5	1	1	-3	4	-2	3	
15	Iso	-9	7	-4	8	-2	-2	-2	6	-13	0	-16	18							91.7
	Dyn	-7	5	-5	4	-3	-4	-2	7	-7	6	-9	9							
16	Iso	-16	3	2	-4	1	1	-2	1	-4	3	-3	0	-4	4	-5	1	-3	1	83.3
	Dyn	1	3	5	4	2	5	0	4	-2	6	-5	4	-1	5	-3	5	-3	3	
17	Iso	-9	0	-8	6	-21	12	-8	-2											87.5
	Dyn	-6	7	-10	9	-8	11	-4	9											
18	Iso	-13	4	-6	6	-10	8	-9	7	-11	11									100
	Dyn	-5	9	-7	3	-7	8	-6	6	-4	6									
19	Iso	-1	10	-6	4	-8	4	2	3	-1	-6	4	-1							66.7
	Dyn	-3	7	-4	9	-4	8	-4	10	-4	8	-5	7							
20	Iso	-1	1	-1	5	-1	-2	-4	3	-2	-1	-2	3	0	-1	-4	5			68.8
	Dyn	-3	4	-3	3	-1	9	1	4	0	6	1	5	-1	2	-1	6			

Table 6. Raw change values of AEMG from isometric measurements and dynamic measurements with the accordance rates between two measurement methods. The unit of change values was %MVC and that of the accordance rate was %.

subj #	Variable	Set1		Set2		Set3		Set4		Set5		Set6		Set7		Set8		Set9		Accordance rate
		2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	2kg	1kg	
1	Iso	13	-6	15	-12	30	-17	13	-5											75
	Dyn	6	1	3	-2	5	-5	0	-3											
2	Iso	8	-4	94	-80	111	-20	97	-62											75
	Dyn	16	1	23	-8	32	-3	-3	-14											
3	Iso	-3	0	11	-5	18	-26	16	-11	16	-10	24	-15							50
	Dyn	10	5	19	-2	15	0	24	9	-2	-2	3	7							
4	Iso	13	1	4	-2	0	0	-1	-2	-3	8	-2	-10							58.3
	Dyn	4	2	3	-1	1	-1	2	0	-1	0	2	1							
5	Iso	15	-7	6	-1	1	0	10	-4	4	-5	7	-5							83.3
	Dyn	8	-2	3	-1	2	0	5	0	3	0	2	0							
6	Iso	16	-10	41	-24	29	-29	36	-39	22	-15	24	-28	20	-6					57.14
	Dyn	3	0	1	1	5	0	2	1	6	0	1	1	3	2					
7	Iso	21	-9	17	-8	-2	2	-1	0	5	2									40
	Dyn	-2	2	2	1	-3	-1	3	-3	-3	2									
8	Iso	0	0	0	0	0	0	0	0	0	0									40
	Dyn	0	0	0	0	0	0	0	0	0	0									
9	Iso	12	-4	11	-11	23	-18	32	-32	46	-21									70
	Dyn	2	1	7	2	7	3	10	-4	11	-1									
10	Iso	0	-6	7	-9	29	-20	13	-3	-11	12	-13	5	-9	14					42.9
	Dyn	2	0	1	1	5	0	9	0	0	1	3	6	0	0					
11	Iso	12	-7	3	4	14	-12	4	-11	4	16									70
	Dyn	1	0	3	-2	3	1	4	-2	2	0									
12	Iso	8	-4	11	-15	12	-8	7	-6	6	-5	12	1							50
	Dyn	-4	4	4	1	2	4	6	-1	0	2	11	5							
13	Iso	24	-31	-6	12	28	-19	-5	26	-7	2	15	-76							58.3

	Dyn	1	2	2	5	4	4	-12	5	7	3	9	4							
14	Iso	11	-10	-4	1	3	-7	0	-2	-3	-2	3	-3	5	-2	1	-2	8	-9	72.2
	Dyn	5	1	4	1	4	-1	3	0	4	0	5	0	5	-1	5	-2	4	-2	
15	Iso	-2	2	10	-12	3	0	-2	-3	0	-7	15	-11							66.7
	Dyn	-10	-8	7	-4	2	-2	4	-3	10	0	4	2							
16	Iso	23	-3	15	-14	15	-14	3	-2	8	-1	19	-6	-5	6	-3	-2	-6	-4	61.1
	Dyn	4	1	2	0	7	1	9	1	13	-2	11	-1	5	1	7	-3	4	-2	
17	Iso	20	-21	16	-4	15	-4	13	-3											62.5
	Dyn	9	-1	9	1	11	1	7	6											
18	Iso	21	2	5	-4	23	-22	10	-7	16	-11									60
	Dyn	9	-2	11	0	6	2	6	-4	7	0									
19	Iso	16	-17	8	-1	11	2	-6	-28	11	15	-19	16							66.7
	Dyn	3	2	-2	6	8	2	2	-2	7	5	-3	4							
20	Iso	-6	1	0	-5	3	-3	10	-6	4	-7	15	-15	8	-8	7	-5			62.5
	Dyn	-1	0	0	0	1	0	0	0	2	0	2	0	-1	1	1	-1			

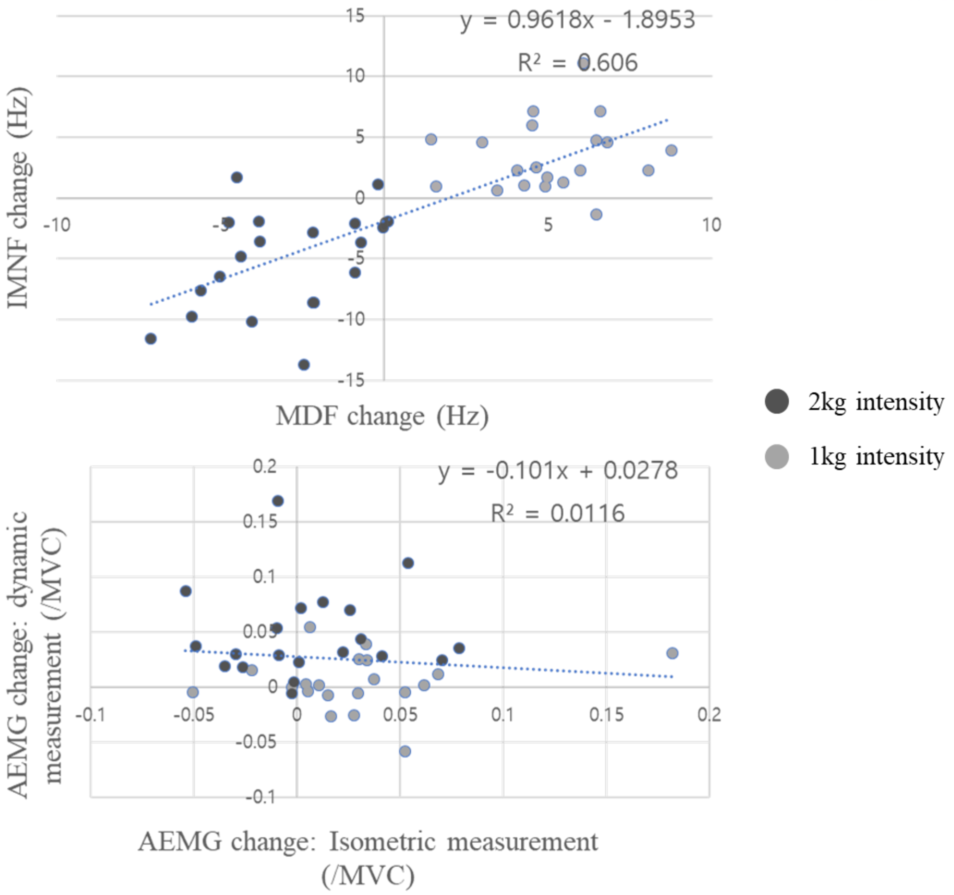

Figure 63. Correlation between fatigue values from isometric and dynamic measurements. (center frequency: top, AEMG: bottom)

4. DISCUSSION

There were two objectives in this study. The first was to evaluate biceps brachii muscle fatigue while changing the intensity of the dynamic muscle contraction continuously. The second was to compare two fatigue evaluation methods each of which were based on isometric and dynamic muscle contraction situations. The study result shows changes in fatigue values following each intensity of fatigue protocols using both evaluations from isometric measurements and dynamic measurements.

Also, there was no effect of intensity of tasks on the peak velocity of elbow flexion and extension. That is, there was no difference in elbow movement between two intensity of fatigue tasks. Considering participants performed consistent elbow flexion and extension regardless of intensity (Figure 14), it is implied that the difference of muscle fatigue changes between two tasks was caused by its intensity, not by the elbow movement.

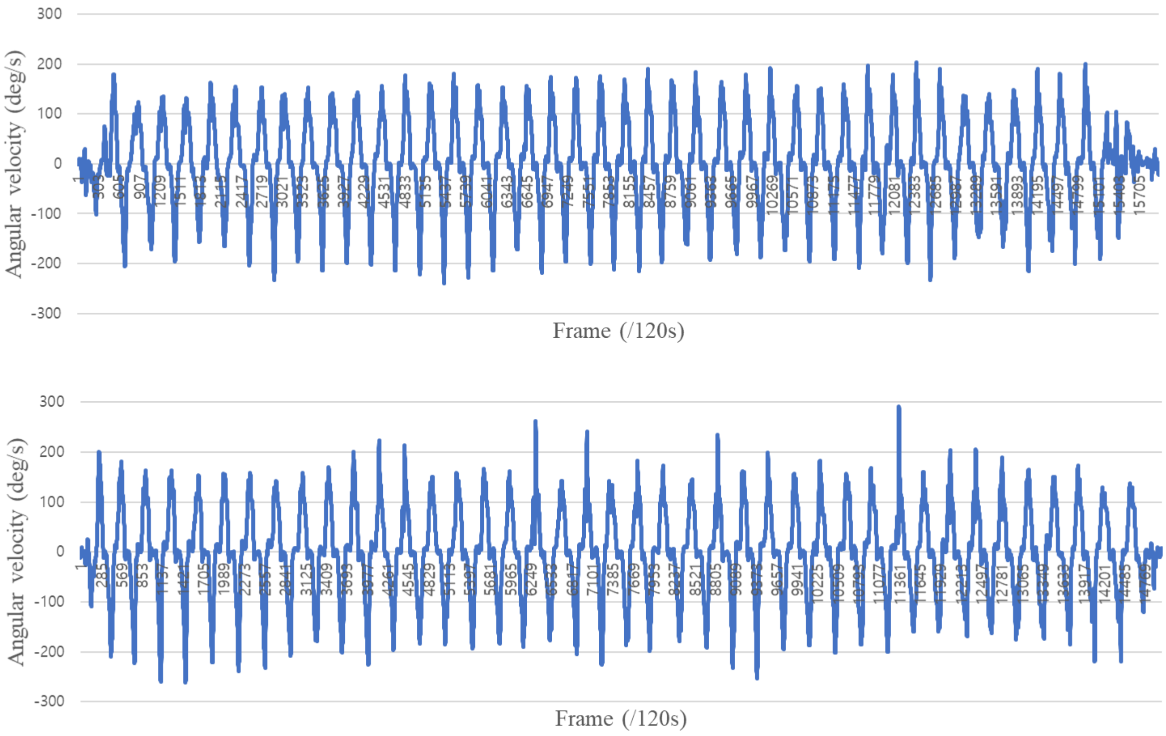

Figure 14. Example data of elbow joint angular velocity while conducting 2kg (top) and 1kg (bottom) intensity task (+: extension, -: flexion).

4.1 Muscle fatigue detection

4.1.1 Detection of development and recovery of muscle fatigue

A significant decrease of MDF and IMNF was detected in 2kg intensity tasks from both isometric and dynamic measurements. Also, a significant increase of MDF and IMNF was detected in 1kg intensity fatigue protocol from isometric and dynamic measurements, respectively. It implies that the established load condition in each intensity of the tasks was proper to induce and recover fatigue on the biceps brachii muscles.

Decrease of the center frequency of biceps brachii muscle shown by MDF and IMNF represents the development of fatigue while participants were performing the 2kg intensity tasks. The decrease is consistent with previous findings that the development of muscle fatigue shifts the frequency spectrum of EMG signal leftward (Cobb & Forbes, 1923; Lippold et al., 1960). The decline of center frequency has most often been attributed to decreases in muscle fiber conduction velocities and selective fatigue of the fast-twitch fibers, caused by increased lactate levels in the fatigued muscle. In the research of Potvin and Bent (1997), from isomeric muscle contraction measurement, the median frequency was reported to be decreased from 72.6 Hz to 53.0 Hz when the muscle was totally fatigued. The median frequency of biceps brachii was also decreased from 75 Hz to 55.7 Hz from dynamic muscle contraction measurement. (Figure 15) Because of the difference in the protocol and data analysis process, it is impossible to compare the absolute value of the center frequency. However, it was confirmed in this experiment that both isometric and dynamic measurements were valid to detect the development of biceps brachii muscle fatigue during the repetitive elbow flexion and extension tasks using 2kg dumbbell. Also, muscle fatigue could be identified in the middle of the development even when the muscle was not totally fatigued.

Center frequency of the biceps brachii muscle was hypothesized to be increased after the 1kg intensity tasks, implying recovery of muscle fatigue. The result from the current study corresponds with a number of previous studies that verified the assessment of muscle fatigue recovery immediately after fatigue tasks using EMG signals. Kuorinka (1988) reported that after isometric biceps brachii muscle contraction (60% MVC) until exhaustion, the EMG spectrum returned rapidly towards starting values at the beginning of the rest period and slowed down reaching a plateau approximately before the fifth minute. (Figure 16) However, Previous studies which investigated the recovery of muscle fatigue were limited to the evaluation of muscle fatigue recovery in rest condition after exercise (Chowdhury et al., 2013; Kuorinka, 1988). The continuous development and recovery of shoulder muscle fatigue following continuous repetition of 20min arm exertion tasks and 5 min rest was investigated from Chowdhury et al. (2013). (Figure 17) However, this was the first study that reported significant recovery of muscle fatigue when muscle load was lowered, maintaining repetitive motion. Compared to studies that just compared the difference in the development of muscle fatigue between relatively high intensity and low intensity muscle contraction (Kuorinka, 1988), this finding gives an insight into the importance of continuous changes of muscle fatigue values following changes of muscle load intensity. In the previous study, repetitive elbow flexion/extension motion using a 1kg dumbbell was reported to occur fatigue on the biceps brachii muscle (Bueno, Lizano, & Montano, 2015). However, in the current study, it was found that biceps brachii muscle recovers from fatigue while conducting elbow flexion and extension using a 1kg load lowered from 2kg. Therefore, it could be concluded that the immediate change of muscle fatigue values while conducting repetitive motion is determined by the ‘relative’ intensity from the previous intensity, not an absolute intensity of the load. The recovery of fatigue in the 1kg intensity fatigue protocol is probably due to the recuperation of the muscle cell metabolism.

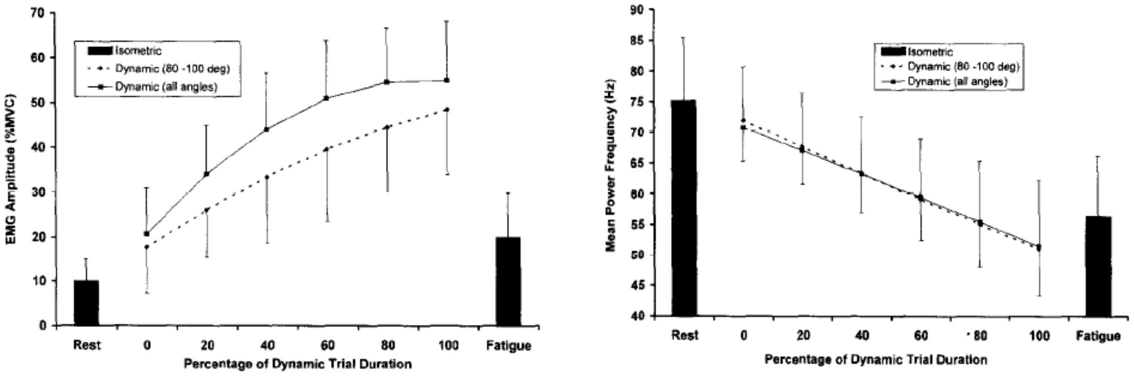

Figure 15. Result of the study from Potvin and Bent (1997). Change of average EMG amplitude (left) and mean power frequency (right) values during fatigue task which were measured from isometric measurement and dynamic trial were presented as graphs. Dyn_{all} represents data from all elbow angle, and Dyn_{80-100} represents data when elbow angle was between 80° and 100° of flexion.

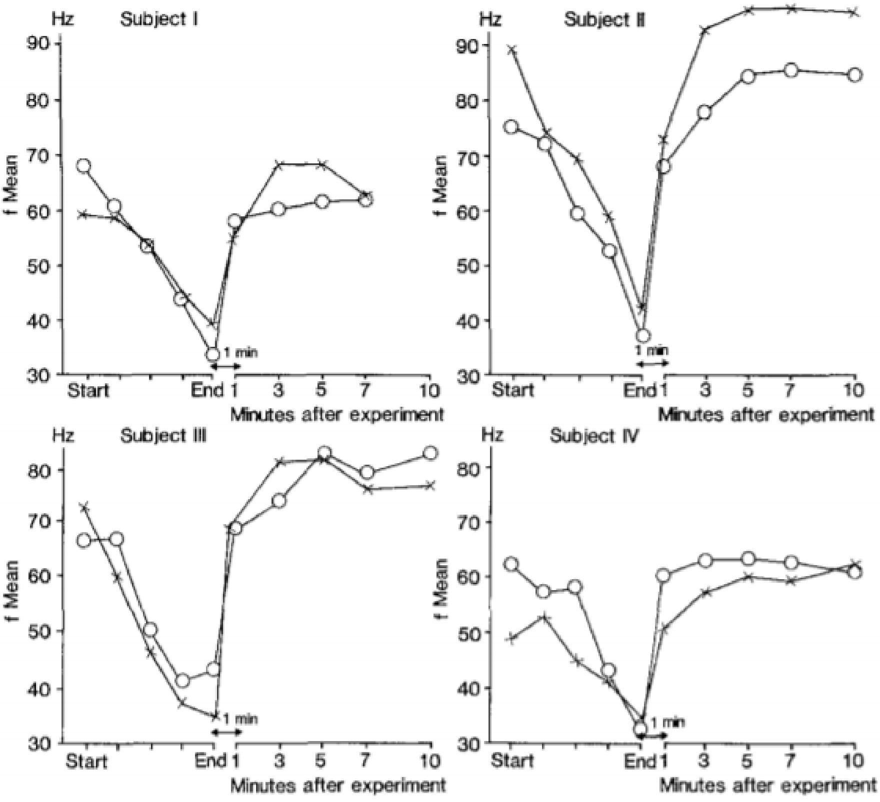

Figure 16. Result of the study from Kuorinka (1988). Change of EMG spectra from biceps during and after isometric exercise were presented in each subject.

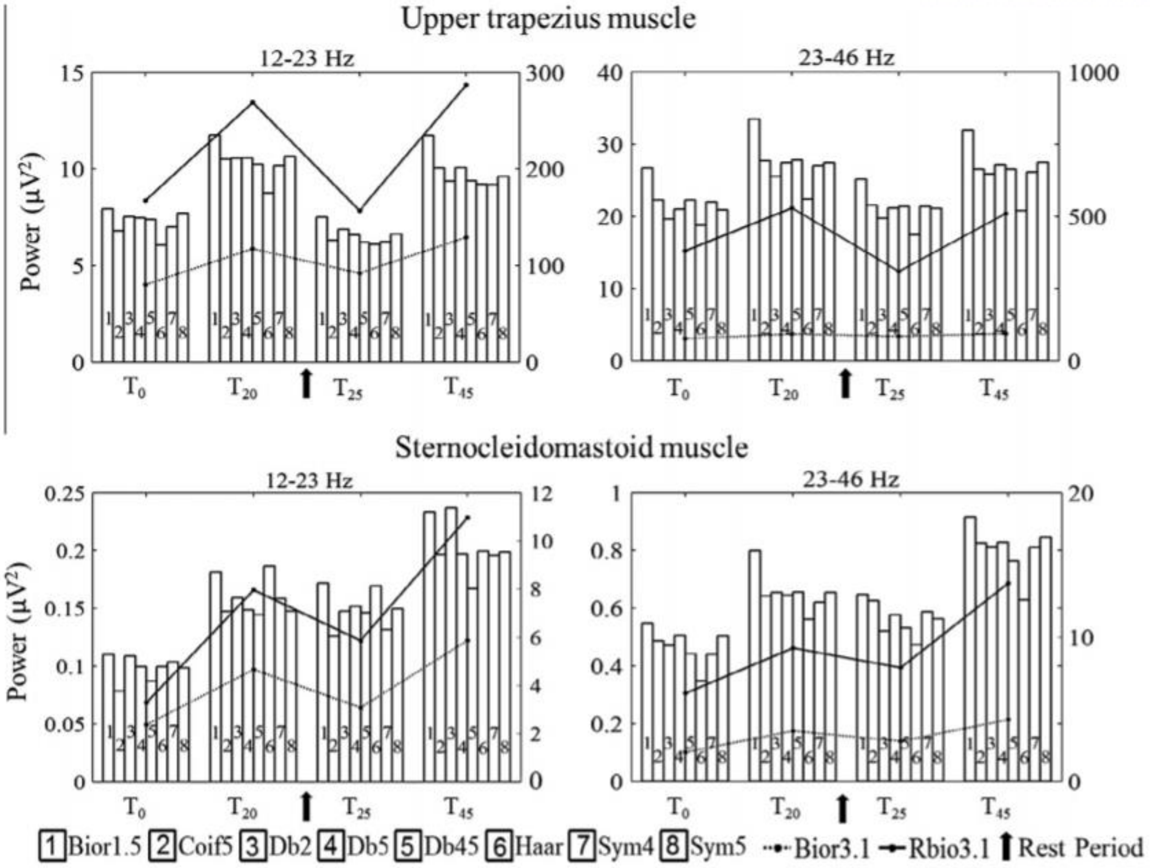

Figure 17. Results of the study from Chowdhury et al. (2013). Mean power in 12–23 Hz and 23–46 Hz frequency bands at different time instances for right upper trapezius and left sternocleidomastoid muscles during repetitive elbow exertion period and rest period. T0, T20, T25, and T45 refer to 1st minute, 20th minute, 25th and 45th minute of the exertions, respectively. Power estimated using Rbio3.1 and Bior3.1 discrete wavelet was plotted using a secondary axis.

However, in case of evaluation of muscle fatigue from AEMG couldn't detect the change of fatigue value sensitively, during tasks. Also, a previous study showed that an increase in EMG amplitude occurred by reduced muscle fiber conduction velocity and shift of EMG signal power spectrum toward lower frequencies. De Luca (1984) And Potvin and Bent (1997) reported that the change of EMG amplitude represents a sensitive index. (Figure 15) The reason for the disagreement between the previous study and the current study seems that the assessment of muscle fatigue by the amplitude of EMG was more influenced by muscle force and, it was less sensitive because it is possible that participants couldn't maintain the posture during the isometric measurement. Several studies pointed out the difficulty of maintaining consistency during isometric muscle fatigue tests (Cifrek et al., 2009). In the case of evaluation of AEMG, the effect of the participant's motion is significant, but it is hard to control their motion in an extremely fatigued situation. Also, it is assumed that muscle fatigue evaluation from EMG amplitude was not sufficient to detect change of muscle fatigue during each set because selected duration (2 min) and load (1, 2kg) in one task was relatively smaller than in previous studies (6kg, average 155 sec in Potvin's experiment (1997). Therefore, muscle fatigue detection should be conducted with other indicators such as frequency value of EMG or muscle stiffness, not only with EMG amplitude itself (Joint Analysis of EMG Spectrum and Amplitude, JASA).

4.1.2 Validity of dynamic muscle fatigue measurements

It is one of the main goals of this study to validate the assessment of muscle fatigue in dynamic muscle contraction situation using continuous wavelet transform, compared to the traditional method with Fourier transform. Therefore, assessment of muscle fatigue was performed in both dynamic muscle contraction situation using Continuous wavelet transform and isometric muscle contraction situation using Fourier transform. The result of this study reports that both assessments detected significant changes in AEMG and center frequency. It implies that both methods are possible to detect the development and recovery of muscle fatigue in each 2kg and1kg intensity task.

Also, the correlation result of the evaluation of muscle fatigue from isometric measurements and dynamic measurements tells that two fatigue detection methods have a strong positive correlation. Considering fatigue detection from isometric measurements as a standard, it is implied that fatigue detection from dynamic measurement using Continuous wavelet transform is as valid as the one from isometric muscle contraction.

Traditionally. isometric contractions have served as the standard for EMG based fatigue quantification, however, it is inevitable to stop the motion and begin the test again to evaluate muscle fatigue using isometric muscle contraction. Therefore, because dynamic measurement using continuous wavelet transform has valid detection of muscle fatigue development and recovery, the method has a big advantage to detect the change of muscle fatigue without interruption of the motion.

Potvin and Bent (1997) investigated a relationship between dynamic and isometric change before and after elbow flexion and extension tasks. They reported that there was no sufficient relationship between isometric changes and dynamic changes in the experiment. (Figure 15) The result does not correspond with the current study's result. It might be because Potvin's study analyzed EMG signal during bicep brachii dynamic contraction using Fast Fourier transform which has been reported to have less sensitivity than Wavelet transform (S. Karlsson et al., 2000). Also, the study was limited to verify muscle fatigue evaluation in dynamic muscle contraction conditions compared to isometric condition. In addition, to confirm the validity and advantage of dynamic muscle fatigue measurement in detecting progress of muscle fatigue, the current study suggests the validity of using dynamic muscle fatigue measurement using Wavelet transform of EMG signals to assess not only the development of muscle fatigue but also that of recovery.

Furthermore, considering the deviation of change value of center frequency, deviation of IMNF change between participants was smaller than the deviation of MDF change at both 2kg and 1kg intensity tasks. F value from ANOVA result which compared the mean difference between the two intensity of tasks was much bigger in IMNF change than in MDF change. It is hard to evaluate the degree of sensitivity of each fatigue assessment method, but it seems that fatigue assessment in dynamic contraction situation using Continuous wavelet transform can quantify muscle fatigue more regularly and distinguish the effect of intensity of muscle load on the fatigue more powerfully than the assessment for isometric muscle contraction situation.

4.2 Implication

The result from the current study suggests a possible application of detecting change of muscle fatigue of industrial workers in the Human-Robot collaboration system to get robot assistance after muscle fatigue. It implies that muscle fatigue of workers would be recovered as the robot assistance is applied to the job after they got fatigued. Previous studies have investigated methods to evaluate muscle fatigue related to Human-Robot collaboration and confirmed their validity (Bai et al., 2012; Hamaya et al., 2017; Peternel et al., 2019). In the concern of the investigation about muscle fatigue detection in Human-robot collaboration system, Bai et al. (2012) and Peternel et al. (2019) suggested methods where the index of frequency features of EMG and muscle force are combined, which was found to be valid to detect the development of muscle fatigue. However, as the investigations were limited to assessing only the accumulation of muscle fatigue, the progress of muscle fatigue after a robot intervention has still remained to question. The result from the current study suggests that robot intervention in form of lowering muscle load after workers get muscle fatigue might reduce muscle fatigue and it can be monitored in dynamic muscle contraction situations without interrupting workers.

By monitoring the development and recovery of muscle fatigue in the Human-robot collaboration system, the external intervention can be controlled to make workers do their job longer and safer, maintaining their superior flexibility/adaptability in the system. Also, understanding the progression and recovery of muscle fatigue following continuously changing muscle load might provide an insight to predict the time that workers could sustain and continue the repetitive manual job in the Human-Robot collaboration system.

4.3 Limitation

Several limitations should be noted in this study. First of all, the weights conditions in which participants should perform their tasks were not selected considering the participant's individual physical ability. Because the capacity of biceps brachii muscle differs by individuals, normalization of the load on the muscle would make the result of the study better to be applied to the real world. Also, the motion of elbow flexion and extension was too restricted in this experiment. Elbow flexion and extension motion in daily life and work environment is usually accompanied by other body parts' movements and not strictly repetitive. Therefore, the result of the current study might not represent the progress of muscle fatigue in the real world.

In this study, all dependent variables were averaged out over the performed sets of each intensity of task for each subject because the number of sets that participants completed differed. Therefore, it was impossible to figure out the effect of time on the change of fatigue values while conducting the whole task. In fact, when comparing fatigue values of the first two sets and the last two sets in each subject, there was no significant difference between the two stages of the task on fatigue values. If it was possible to normalize the number of sets or make muscle load conditions in which participants are totally exhausted at the same duration, it would be better to interpret the effect of time on the progression of fatigue following the continuous change of muscle load.

Also, the muscle load condition was limited to only two levels (2kg, and 1kg). Assuming Human-robot collaboration system can provide the multi-level intensity of external assistance, the result of this research have limitation to estimate the tendency of change in muscle fatigue following the external intervention. Furthermore, diverse factors affecting muscle fatigue also neede to be considered to provide a better insight into the progression of muscle fatigue during the task and to the estimation of the duration that an individual can sustain. In this study, restricted participants were recruited (males who do light exercise more than once a week). Therefore, the result might not be applied to all range of gender and physical condition.

5. CONCLUSION

The principal aim of the current study was to evaluate biceps brachii muscle fatigue while changing the intensity of the dynamic muscle contraction continuously and to compare two fatigue evaluation methods each of which were based on isometric and dynamic muscle contraction situation. The study result shows that muscle fatigue was increased when conducting a 2kg intensity of fatigue task, but it was decreased when conducting 1kg intensity of fatigue task right after the 2kg intensity task. Therefore, it was concluded that the immediate change of muscle fatigue values while conducting repetitive motion is determined by the 'relative' intensity from the previous intensity, not by an absolute intensity of the load.

Also, it was revealed that muscle fatigue measurement in dynamic muscle contraction situation using Continuous wavelet transform can detect muscle fatigue as precisely as the measurement in isometric muscle contraction situation. Both the development and recovery of muscle fatigue were detected from both dynamic measurement and isometric measurement.

The result from the current study suggests a possible application of detecting change of muscle fatigue of industrial workers in the Human-Robot collaboration system to enable robot assistance after muscle fatigue. Progressed from previous studies, the current study suggests that robot intervention in form of lowering muscle load after workers got muscle fatigue might reduce muscle fatigue and it can be monitored in dynamic muscle contraction situations without interrupting workers.

To broaden these findings, further studies about muscle fatigue monitoring in which diverse individual physical conditions and multi-level of muscle load are considered need to be conducted. They may enable estimation of the duration for which an individual can sustain with a defined load by taking into account the muscle load factor with diverse factors affecting muscle fatigue such as gender, muscle mass or psychological factors.

References

Akagi, R., Fukui, T., Kubota, M., Nakamura, M., & Ema, R. (2017). Muscle Shear Moduli Changes and Frequency of Alternate Muscle Activity of Plantar Flexor Synergists Induced by Prolonged Low-Level Contraction. *Front Physiol, 8*, 708. doi:10.3389/fphys.2017.00708

Bai, F., Lubecki, T. M., Chew, C.-M., & Teo, C.-L. (2012). *Novel Time-Frequency Approach for Muscle Fatigue Detection Based on sEMG*.

Bi, L., Feleke, A. G., & Guan, C. (2019). A review on EMG-based motor intention prediction of continuous human upper limb motion for human-robot collaboration. *Biomedical Signal Processing and Control, 51*, 113-127. doi:https://doi.org/10.1016/j.bspc.2019.02.011

Brody, L. R., Pollock, M. T., Roy, S. H., De Luca, C. J., & Celli, B. (1991). pH-induced effects on median frequency and conduction velocity of the myoelectric signal. *J Appl Physiol (1985), 71*(5), 1878-1885. doi:10.1152/jappl.1991.71.5.1878

Broman, H. (1977). An investigation on the influence of a sustained contraction on the succession of action potentials from a single motor unit. *Electromyogr Clin Neurophysiol, 17*(5), 341-358.

Bueno, D. R., Lizano, J. M., & Montano, L. (2015, 25-29 Aug. 2015). *Muscular fatigue detection using sEMG in dynamic contractions.* Paper presented at the 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).

Chowdhury, S. K., Nimbarte, A. D., Jaridi, M., & Creese, R. C. (2013). Discrete wavelet transform analysis of surface electromyography for the fatigue assessment of neck and shoulder muscles. *J Electromyogr Kinesiol, 23*(5), 995-1003. doi:10.1016/j.jelekin.2013.05.001

Cifrek, M., Medved, V., Tonkovic, S., & Ostojic, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clin Biomech (Bristol, Avon), 24*(4), 327-340. doi:10.1016/j.clinbiomech.2009.01.010

Cobb, S., & Forbes, A. (1923). ELECTROMYOGRAPHIC STUDIES OF MUSCULAR FATIGUE IN MAN. *American Journal of Physiology-Legacy Content, 65*(2), 234-251. doi:10.1152/ajplegacy.1923.65.2.234

De Luca, C. J. (1984). Myoelectrical manifestations of localized muscular fatigue in humans. *Crit Rev Biomed Eng, 11*(4), 251-279.

Dieterich, A. V., Andrade, R. J., Le Sant, G., Falla, D., Petzke, F., Hug, F., & Nordez, A. (2017). Shear wave elastography reveals different degrees of passive and active stiffness of the neck extensor muscles. *Eur J Appl Physiol, 117*(1), 171-178. doi:10.1007/s00421-016-3509-5

Dresner, M. A., Rose, G. H., Rossman, P. J., Muthupillai, R., Manduca, A., & Ehman, R. L. (2001). Magnetic resonance elastography of skeletal muscle. *J Magn Reson Imaging, 13*(2), 269-276. doi:10.1002/1522-2586(200102)13:2<269::aid-jmri1039>3.0.co;2-1

Eby, S. F., Cloud, B. A., Brandenburg, J. E., Giambini, H., Song, P., Chen, S., . . . An, K. N. (2015). Shear wave elastography of passive skeletal muscle stiffness: influences of sex and age throughout adulthood. *Clin Biomech (Bristol, Avon), 30*(1), 22-27. doi:10.1016/j.clinbiomech.2014.11.011

Enoka, R. M. (1995). Mechanisms of muscle fatigue: Central factors and task dependency. *J*

Electromyogr Kinesiol, 5(3), 141-149. doi:10.1016/1050-6411(95)00010-w

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *J Physiol, 586*(1), 11-23. doi:10.1113/jphysiol.2007.139477

Farina, D., Fattorini, L., Felici, F., & Filligoi, G. (2002). Nonlinear surface EMG analysis to detect changes of motor unit conduction velocity and synchronization. *J Appl Physiol (1985), 93*(5), 1753-1763. doi:10.1152/japplphysiol.00314.2002

Farina, D., Fosci, M., & Merletti, R. (2002). Motor unit recruitment strategies investigated by surface EMG variables. *J Appl Physiol (1985), 92*(1), 235-247. doi:10.1152/jappl.2002.92.1.235

Farina, D., Merletti, R., & Disselhorst-Klug, C. (2004). Multi-Channel Techniques for Information Extraction from the Surface EMG. In *Electromyography* (pp. 169-203).

Hamaya, M., Matsubara, T., Noda, T., Teramae, T., & Morimoto, J. (2017). Learning assistive strategies for exoskeleton robots from user-robot physical interaction. *Pattern Recognition Letters, 99*, 67-76. doi:https://doi.org/10.1016/j.patrec.2017.04.007

Hermens, H., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol, 10*, 361-374. doi:10.1016/S1050-6411(00)00027-4

Hostens, I., Seghers, J., Spaepen, A., & Ramon, H. (2004). Validation of the wavelet spectral estimation technique in Biceps Brachii and Brachioradialis fatigue assessment during prolonged low-level static and dynamic contractions. *Journal of Electromyography and Kinesiology, 14*(2), 205-215. doi:https://doi.org/10.1016/S1050-6411(03)00101-9

Karlsson, J. S., Gerdle, B., & Akay, M. (2001). Analyzing surface myoelectric signals recorded during isokinetic contractions. *IEEE Engineering in Medicine and Biology Magazine, 20*(6), 97-105. doi:10.1109/51.982281

Karlsson, S., Yu, J., & Akay, M. (2000). Time-frequency analysis of myoelectric signals during dynamic contractions: a comparative study. *IEEE Trans Biomed Eng, 47*(2), 228-238. doi:10.1109/10.821766

Koenig, I., Eichelberger, P., Blasimann, A., Hauswirth, A., Baeyens, J.-P., & Radlinger, L. (2018). Wavelet analyses of electromyographic signals derived from lower extremity muscles while walking or running: A systematic review. *PLOS ONE, 13*(11), e0206549. doi:10.1371/journal.pone.0206549

Komi, P., & Tesch, P. (1979). EMG frequency spectrum, muscle structure, and fatigue during dynamic contraction in man. *European Journal of Applied Physiology and Occupational Physiology, 42*, 41-50. doi:10.1007/BF00421103

Kuorinka, I. (1988). Restitution of EMG spectrum after muscular fatigue. *European Journal of Applied Physiology and Occupational Physiology, 57*(3), 311-315. doi:10.1007/BF00635989

Kwatny, E., Thomas, D. H., & Kwatny, H. G. (1970). An Application of Signal Processing Techniques to the Study of Myoelectric Signals. *IEEE Transactions on Biomedical Engineering, BME-17*(4), 303-313. doi:10.1109/TBME.1970.4502758

Larivière, C., Arsenault, A. B., Gravel, D., Gagnon, D., & Loisel, P. (2002). Evaluation of measurement strategies to increase the reliability of EMG indices to assess back muscle fatigue and recovery. *Journal of Electromyography and Kinesiology, 12*(2), 91-102. doi:https://doi.org/10.1016/S1050-6411(02)00011-1

Lippold, O. C. J., Redfearn, J. W. T., & VuČO, J. (1960). THE ELECTROMYOGRAPHY OF FATIGUE. *Ergonomics, 3*(2), 121-131. doi:10.1080/00140136008930474

Peternel, L., Fang, C., Tsagarakis, N., & Ajoudani, A. (2019). A selective muscle fatigue management approach to ergonomic human-robot co-manipulation. *Robotics and Computer-Integrated Manufacturing, 58*, 69-79. doi:https://doi.org/10.1016/j.rcim.2019.01.013

Petrofsky, J. S., & Lind, A. R. (1980). Frequency analysis of the surface electromyogram during sustained isometric contractions. *European Journal of Applied Physiology and Occupational Physiology, 43*(2), 173-182. doi:10.1007/BF00422448

Potvin, J., & Bent, L. (1997). A validation of techniques using surface EMG signals from dynamic contractions to quantify muscle fatigue during repetitive tasks. *J Electromyogr Kinesiol, 7*, 131-139. doi:10.1016/S1050-6411(96)00025-9

APPENDICES

APPENDIX A

Full Analysis of Variance Tables (Compare pre vs post value)

Pre vs post MDF value from isometric measurements during 2kg intensity tasks

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	7113.8	374.409	42.24	0
pre vs post	1	274.3	274.262	30.94	0
Error	19	168.4	8.865		
Total	39	7556.5			

Pre vs post MDF value from isometric measurements during 1kg intensity tasks

Source	DF	Adj SS	Adj MS	F-Value	P-Value
participants	19	7538.28	396.751	93.97	0
pre vs post	1	118.12	118.115	27.98	0
Error	19	80.22	4.222		
Total	39	7736.61			

Pre vs post AEMG value from isometric measurements during 2kg intensity tasks

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	2.66818	0.14043	135.16	0
pre vs post	1	0.00873	0.008731	8.4	0.009
Error	19	0.01974	0.001039		
Total	39	2.69665			

Pre vs post AEMG value from isometric measurements during 1kg intensity tasks

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Participants	19	2.05905	0.108371	160.35	0
pre vs post	1	0.00032	0.000317	0.47	0.501
Error	19	0.01284	0.000676		
Total	39	2.07221			

Pre vs post IMNF value from dynamic measurements during 2kg intensity tasks

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
participants	19	2135.66	112.403	48.15	0
pre vs post	1	91.85	91.853	39.34	0
Error	19	44.36	2.335		
Total	39	2271.87			

Pre vs post IMNF value from dynamic measurements during 1kg intensity tasks

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
participants	19	1512.81	79.622	43.98	0
pre vs post	1	260.12	260.117	143.69	0
Error	19	34.4	1.81		
Total	39	1807.33			

Pre vs post AEMG value from dynamic measurements during 2kg intensity tasks

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
participants	19	0.84962	0.044717	54.02	0
pre vs post	1	0.02308	0.023081	27.88	0
Error	19	0.01573	0.000828		
Total	39	0.88843			

APPENDIX B

Full Analysis of Variance Tables (Compare 2kg vs 1kg intensity in change values)

2kg vs 1kg intensity in AEMG change value from isometric measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.037258	0.001961	1.34	0.267
Intensity	1	0.005718	0.005718	3.89	0.006
Error	19	0.027907	0.001469		
Total	39	0.070883			

2kg vs 1kg intensity in MDF change value from isometric measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	52.22	2.749	0.12	1
Intensity	1	752.35	752.347	32.12	0
Error	19	445.06	23.424		
Total	39	1249.63			

2kg vs 1kg intensity in AEMG change value from dynamic measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.01543	0.000812	0.56	0.894
Intensity	1	0.01936	0.019358	13.29	0.002
Error	19	0.02767	0.001456		
Total	39	0.06246			

2kg vs 1kg intensity in IMNF change value from dynamic measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	59.92	3.154	0.61	0.852
Intensity	1	661.12	661.115	128.72	0
Error	19	97.58	5.136		
Total	39	818.62			

ACKNOWLEDGMENTS

As a checkpoint of a long journey, I got a master’s degree. In the journey so far, I was able to have many amazing experiences, and they have grown me up. Thanks to many people who have been around me, the process has been happy to me, and I’m expecting there will be more good things to do with them in the future.

First of all, I would like to sincerely appreciate to my advisor, professor Gwanseob Shin. Every opportunity and support that he gave to me was a springboard for my growth, and countless advice from him always made me inspired. I feel big pride in being one of his students. I will always do my best to be a student worthy of that pride. Also, I really appreciate to valuable advice and assistance from professor Sang Hoon Kang and professor Oh-Sang Kwon.

The time in Ergolab is full of joy because of dear lab members. Hwayeong, Jeongmin, Nakyung, Haerim, and Hyeseon, they helped me to adapt well to Ergolab and I can study in an excellent condition which had been established from them. Thank you. Seobin and Eunji, thank you for leading lab members and give countless guides to us as a senior. Because of their great works, sometimes I even feel a big burden to replace them. They are irreplaceable. Misol and my friend Donghyun, it was a good fortune for me to enter graduate school with them. The studies, experiments and business trips were happy for me to be with them, no matter how hard they were, thank you. Soonyeong, Hyolim and Dasom, thank you to support eonni and obba. I hope you achieve your goals well in Ergolab, and I’m always willing to help you. My muse Eugene, thank you for always standing by my side and cheer me up.

Finally, I am grateful to my family and friends for giving me continuous encouragement. Especially, I really appreciate to unconditional love and support from mom, dad, and Chanjin. Without them, my every accomplishment would not have been possible. Thank you.