A Simplified Analysis of Real-time Monitoring of Muscle Contraction during Dynamic Exercise Using an MMG/EMG Hybrid Transducer System

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Abstract To evaluate muscle function accurately, it is necessary to simultaneously measure electromyogram (EMG) and mechanomyogram (MMG). We have developed an MMG/EMG hybrid transducer system that can simultaneously measure displacement-MMG (dMMG) and EMG, and reported that the dMMG and EMG measurements reflect muscle strength during dynamic exercise. The analysis of dMMG and EMG in our previous studies only calculated the total power spectrum obtained from discrete Fourier transform (DFT). Using this method of analysis, however, it is difficult to present information on muscle contraction in real time during exercise because of high computational cost due to huge amount of computation by DFT. In the present study, we propose a simplified method to evaluate muscle contraction during dynamic exercise by directly processing dMMG and EMG in the time domain. We adapted the dMMG/EMG data during recumbent bicycle pedaling obtained in our previous study to perform time-domain analysis. The novel time-domain analysis yielded equivalent results as those of previous analysis, and reflected muscle contraction during dynamic exercise. In addition, because dMMG and EMG by the proposed analysis increased with load increase during prolonged pedaling, it may be suitable for real-time monitoring of muscle function. The proposed method not only accurately measures muscle function during dynamic exercise in real time but also has a significantly lower computational cost.

Keywords: mechanomyogram, electromyogram, real-time monitoring, displacement-MMG.


1. Introduction

Aging causes decreases in muscle mass, muscle strength, and physical function, which is known as sarcopenia [1, 2]. Daily exercise is indispensable for the prevention of muscle weakness. To confirm the effect of daily exercise and provide motivation for the continuation of exercise, a method that can easily measure and evaluate muscle strength and motor function is required. The manual muscle test is generally used to evaluate muscle strength, but the evaluation is not very reliable since it may vary depending on the examiner [3]. Mechanomyogram (MMG) is considered to be a non-invasive method capable of quantitative measurements [4–7]. In the process of muscle contraction, electromyogram (EMG) and MMG have an input-output relationship [8]. Accordingly, simultaneous measurement of MMG and EMG allows detailed evaluation of the function of muscle contraction. We developed a novel MMG/EMG hybrid transducer system and an analysis method that can simultaneously evaluate MMG and EMG during dynamic exercise were developed [9, 10]. Our study showed that measurements using the MMG/EMG hybrid transducer system reflected muscle strength during dynamic exercise [10]. The analysis of MMG and EMG used in the previous study was a frequency analysis using discrete Fourier transform (DFT). Because this analysis method requires a huge amount of calculation for muscle function evaluation, the analysis has to be done off-line after measurement of dMMG and EMG. Due to the high computational cost, it is difficult to present the muscle function analysis results immediately to the exercisers and trainers in the clinical and sports fields. In order to realize real-time monitoring of muscle function during dynamic exercise, it is necessary to reduce the computational cost.

To solve this problem, we focused on the fact that the square sum of the time domain and the square sum of absolute values of Fourier coefficients are equal. This...
study aimed to introduce time-domain analysis to evaluate muscle contraction more conveniently from MMG and EMG measured using the MMG/EMG hybrid transducer system. Time-domain analysis was compared with frequency-domain analysis using data of recumbent bicycle pedaling obtained in previous studies [10]. In addition, the time-domain measurement for prolonged exercise and the possibility of real-time monitoring of muscle contraction evaluation during dynamic exercise were analyzed.

2. Methods

2.1 MMG/EMG hybrid transducer system

Figure 1 shows the MMG/EMG hybrid transducer system. This system is configured with a MMG/EMG transducer and measurement software. The transducer and measuring terminals are wirelessly connected by Bluetooth. Therefore, MMG and EMG can be easily measured by anyone at the bedside or clinic. It has many applications in the field of medicine and sports. The disposable electrodes attached to the skin are used for EMG measurement. In MMG, the distance between the MMG sensor (photo reflector) and skin surface is measured, and defined as displacement-MMG (dMMG). The dMMG reflects expansion or contraction of the physiological cross-sectional area [10].

2.2 Experiment I

The dMMG and EMG were acquired from a subject while pedaling on a recumbent bicycle. Data for comparison of time- and frequency-domain analyses were based on the data published in previous study [10]. The dMMG and EMG data were obtained using the MMG/EMG hybrid transducer when four healthy subjects (age, 25.5 ± 7.0 years, subjects 1–4) pedaled at 60 rpm on a recumbent bicycle. The target muscle was the vastus medialis (VM) of the right foot. Pedaling loads of 51, 68, 80, 99 and 108 W as well as passive pedaling (when the evaluator turned the pedal without the subject’s voluntary contraction) were tested. The measurements were performed four times for 10 s per load. The dMMG and EMG data were sampled at 1,000 Hz.

2.3 Experiment II

One healthy subject participated in the experiment. The subject was 38 years of age (subject 5). The target muscle was VM, the same as in Experiment I. The subject was seated on a recumbent bicycle (C545R, SportsArt, Mukilteo, WA, USA), and both the toes and instep were secured with a belt. Before attaching the transducer, the skin was prepared by rubbing the surface with a skin preparation gel for stable electrode contact. The MMG/EMG hybrid transducer was attached to the center of the muscle, and was secured with a dedicated belt as shown Fig. 1. The subject pedaled at 60 rpm using a metronome, without moving the upper body. The dMMG and EMG were recorded for 150 s from the start of measurement. The pedaling load was increased continuously in the order 51, 68, 80, 99 and 108 W every 30 s during the exercise. Finally, passive pedaling was measured as in Experiment I. The sampling frequency was 1,000 Hz.

This study was conducted according to the principles of the Declaration of Helsinki, and ethical approval for the experiments was granted by the Okayama University Ethics Committee (approval number 1703-013). All subjects received sufficient explanations about the experiment and provided informed consent.

2.4 Analysis methods

Figure 2 shows the methods of time-domain and frequency-domain analyses. The target waveform was three periods of synchronized dMMG and EMG. After subtracting the original waveform, the average value was converted to a waveform centered on zero. In the frequency-domain analysis, after obtaining the power spectrum by DFT with a Hamming window, the dMMG and EMG were calculated as the total power (area value) of the power spectrum below 100 Hz. The dMMG and EMG were directly calculated as the square sum of the targeted raw dMMG and EMG waveforms.

For experiments of prolonged pedaling with continuous load change (Experiment II), the time-domain analysis period was set at every 2 s, as shown in Fig. 3, and dMMG and EMG were analyzed continuously from 0 s to 150 s.

The dMMG and dMMG were normalized by the average values obtained during passive pedaling for both methods of analysis (n-dMMG, n-dMMG), and the EMG and EMG were normalized by the minimum value excluding passive pedaling for both methods (n-EMG, n-EMG).
2.5 Statistical analysis

Data are expressed as mean ± SD, and were analyzed using SPSS Statistics 24.0 (IBM, Armonk, NY, USA). Differences between the two groups across the work rate (frequency-domain analysis versus time-domain analysis) were assessed by two-way factorial ANOVA. Correlation was determined using the Pearson correlation test. *P* values less than 0.05 were considered statistically significant.

3. Results

3.1 Comparison between time-domain analysis and frequency-domain analysis

At all pedaling loads, dMMG_TD and EMG_TD were significantly greater than dMMG_FD and EMG_FD (*p* < 0.01), as shown in Fig. 4A, B. In exercises involving joint motion, the cross-sectional area increases even by passive exercise (not exerting power). In other words, the signals of dMMG_TD and dMMG_FD generated by exercising and performing joint motion contain the passive movement component. Therefore, normalizing dMMG_TD and dMMG_FD by subtracting passive pedaling data reflected muscle contraction strength during dynamic exercise. Figure 5A shows dMMG_TD and dMMG_FD normalized by passive pedaling, and Fig. 5B shows EMG_TD and EMG_FD normalized by the minimum value. There were no differences between n-dMMG_TD and n-dMMG_FD (*p* = 0.810) and between n-EMG_TD and n-EMG_FD (*p* = 0.840). These results indicated that time- and frequency-domain analyses yielded equivalent results in muscle contraction evaluation during dynamic exercise.

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Fig. 2 Processing of dMMG and EMG data by time-domain analysis and frequency-domain analysis.

Fig. 3 Analysis method of time-domain for prolonged pedaling. Analysis period was set at 2 s for raw waveforms of dMMG and EMG.

Fig. 4 Results of dMMG_TD, dMMG_FD (A) and EMG_TD, EMG_FD (B) by time-domain analysis and frequency-domain analysis. Data are expressed as mean ± SD. **: *p* < 0.01

Fig. 5 Normalized data: n-dMMG_TD, n-dMMG_FD and n-EMG_TD, n-EMG_FD after eliminating the influence of passive pedaling from dMMG and EMG analyzed by time-domain analysis and frequency-domain analysis. Data are means ± SD. N.S.: not significant.
3.2 Relationship between time-domain analysis and frequency-domain analysis of each subject

The relationship between n-dMMG<sub>TD</sub> and n-dMMG<sub>FD</sub> is shown in Fig. 6A, and the relationship between n-EMG<sub>TD</sub> and n-EMG<sub>FD</sub> is shown in Fig. 6B for each subject. A strong positive correlation with a correlation coefficient of approximately 1.0 was observed in all the subjects.

3.3 Relationship between pedaling load and n-dMMG<sub>TD</sub>, n-EMG<sub>TD</sub>

The n-dMMG<sub>TD</sub> and n-EMG<sub>TD</sub> were linearly approximated and showed a strong positive correlation with the pedaling work rate (Fig. 7). There was no contradiction with previous reports on MMG and EMG measurements in cycle ergometry [11–13]. Reasonable results were achieved for the relationship between exercise load and muscle strength.

3.4 Continuous analysis of time-domain analysis during prolonged pedaling

The raw waveforms of dMMG and EMG are shown in Fig. 8, and time series of the n-dMMG<sub>TD</sub> and n-EMG<sub>TD</sub> for VM adapted to time-domain analysis every 2 s are shown in Fig. 9, where the dMMG<sub>TD</sub> and EMG<sub>TD</sub> are continuously plotted every 2 s. In addition, average n-dMMG<sub>TD</sub> and n-EMG<sub>TD</sub> for each load are shown in Fig. 9 (right). The analysis period of time-domain analysis was the same as the pedaling cycle. The n-dMMG<sub>TD</sub> and n-EMG<sub>TD</sub> for VM increased along with load increase. Even though the analysis period of 2 s was shorter than that in Experiment I, which was approximately 10 s, the n-dMMG/n-EMG indicated the behavior of
muscle contraction in response to the pedaling load. In other words, it precisely detected the temporal changes in muscle contraction during dynamic exercise.

4. Discussion

The present study demonstrated that (1) n-dMMGTD, n-EMGTD, n-dMMGFD, and n-EMGFD were equivalent; (2) the relationship between n-dMMGTD and n-dMMGFD and the relationship between n-EMGTD and n-EMGFD in each subject showed a strong positive correlation. In fact, the correlation coefficient was almost 1.0; (3) n-dMMGTD and n-EMGTD correlated with pedaling load; and (4) n-dMMGTD and n-EMGTD reflected muscle contraction according to pedaling load in continuous analysis during prolonged pedaling. To the best of our knowledge, this study is the first to evaluate muscle contraction during dynamic exercise by directly analyzing the time-domain of dMMG and EMG using the MMG/EMG hybrid transducer system.

4.1 Evaluation of muscle contraction using time-domain analysis during dynamic exercise

There are numerous studies on signal processing methods for evaluating the MMG of voluntary contraction. Typical methods are root mean square (RMS) [14, 15], average rectified value (ARV) [16, 17], integrated MMG, [18, 19] and frequency analysis [20, 21]. There are also a number of studies that evaluated MMGs during dynamic exercise using these methods. In reports regarding signal processing during dynamic exercise, Shinohara et al. [12] and Perry et al. [13] evaluated MEA measured using a condenser microphone or piezo contact sensor during ergometer pedaling with RMS signal processing. On the other hand, muscle strength evaluation during dynamic exercise by frequency analysis of dMMG acquired with an MMG/EMG hybrid transducer system was discussed. Attempts were made to evaluate muscle contraction by calculating the total power of the power spectrum acquired using DFT of raw dMMG waveform. The dMMG captured the uniaxial displacement and vibration component of muscle contraction, and the calculated total power is speculated to represent the sum of output energy of the muscles during dynamic exercise [10]. The information provided by power spectra of MMG and EMG by DFT or fast Fourier transform is useful for evaluating muscle contraction. Evaluations of muscle function and fatigue by mean power frequency and median power frequency of MMG using a conventional transducer have been reported [22–26]. However, providing clinicians and trainers real-time frequency analysis information on muscle function of sustained dynamic exercise is very difficult owing to high computational cost due to huge amount of calculation by DFT.

Regardless whether the signal is expressed in time domain or frequency domain, its square sum and the integrated power spectrum are equal, representing the total energy of the signal. Therefore, the time domain of square sums of dMMG and EMG is likely to be equivalent to the analysis method in the previous report [10]. Time-domain analysis reduces the computational cost considerably because it only requires the sum of squares of the time function, and is hence cost-effective. The dMMGTD had a characteristic that expresses the energy of muscle contraction itself, and a physical significance different from signal processing such as RMS and ARV. In addition, this analysis calculates the energy of dMMG and EMG of muscle contraction during the whole exercise and does not require analysis of the feature value of waveform amplitude as RMS and ARV. Moreover, it is a very simple analysis that does not involve rectification or low-pass filter. To reduce the computational cost, Al-Timemy et al. [27] evaluated the force variation of the prosthetic limb by directly processing the time domain of EMG measured from transradial amputees. It was assumed that dMMG and EMG analyzed in time domain during dynamic exercise are equivalent to frequency-domain analysis. Although dMMGFD decreased significantly compared to dMMGTD, the cause of this may...
be the influence of the window function used for DFT (Fig. 4). It is believed that both ends of the window subject to DFT are attenuated. In fact, dMMGTD without the Hamming window and dMMGTD were almost equal as shown in Table 1, and the difference was not statistically significant. Interestingly, no difference was observed after normalizing by passive pedaling. These results indicate that time- and frequency-domain analyses are equivalent in muscle contraction evaluation during dynamic exercise. In exercises involving joint motion, the cross-sectional area increases even by passive exercise (not exerting power). In other words, the signals of dMMGTD and dMMGFD produced by exercise involving joint motion contain the passive movement component. As reported previously, n-dMMGFD reflects only the substantial muscle strength by dynamic exercise [10]. This result shows that n-dMMGTD obtained by time-domain analysis also detects the muscle strength component by muscle contraction during dynamic exercise. In essence, n-dMMGTD represents the output energy of the muscle by exercise. Additionally, time-domain analysis can directly analyze the raw waveforms of dMMG and EMG measured with an MMG/EMG hybrid transducer system and reflect the output energy of the muscle without omission. From the above, n-dMMGTD and n-EMGTD may be used to reflect muscle contraction more accurately during dynamic exercise than frequency-domain analysis. We found that n-dMMGTD and n-EMGTD correlated strongly with n-dMMGFD and n-EMGFD, respectively. Surprisingly, the correlation coefficient of all subjects was nearly 1.0 (Fig. 6). These results provide evidence that time-domain analysis is a useful tool for muscle contraction evaluation even at individual level. The results confirm that time-domain analysis is also a practical tool for muscle contraction evaluation during dynamic exercise using the MMG/EMG hybrid transducer system. The n-dMMGTD and n-EMGTD evaluated muscle strength during pedaling on a recumbent bicycle (Fig. 7). Both correlate strongly with the pedaling load with linear approximation, indicating that n-dMMGTD and n-EMGTD reflect the increase in pedal load; that is, the increase in muscle strength. This result is consistent with our previous reports [10] and other reports of dynamic MMG measurements [11–13], and is also a reasonable result from the viewpoint of exercise physiology [28].

4.2 Real-time monitoring of muscle contraction during dynamic exercise

Real-time monitoring of muscle contraction using time-domain analysis was demonstrated (Fig. 9). As mentioned above, dMMGTD expresses output energy of muscle during exercise. Understandably, exercisers cannot continue exercising without increasing muscle output energy when the exercise load is increased during continuous exercise. In this experiment, the pedaling load was set in 5 steps during prolonged exercise (150 s), and the time domain period was set at every 2 s. Real-time monitoring of dMMGTD and EMGTD reflects muscle strength and action potential to maintain pedaling. As a result, n-dMMGTD and n-EMGTD increase with exercise load, and the relationship between exercise load and muscle output energy can be properly expressed. These results indicate the possibility of real-time monitoring of muscle contraction by time-domain analysis during dynamic exercise using the MMG/EMG hybrid transducer system. However, there are no reported examples that quantitatively evaluate prolonged muscle contraction in real-time using dMMG and EMG.

Real-time monitoring of muscle contraction during prolonged exercise was successfully evaluated using time-domain analysis in this study. However, the setting of the analysis period should be noted. In this analysis, the time domain of analysis was set at the same duration as the pedaling cycle (2 s). Due to slight differences between pedaling cycles, the raw waveforms of dMMG and EMG entering the analysis window may be slightly varied. Therefore, there is a possibility of error during real-time monitoring. To address this issue, it is neces-

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Table 1 Comparison of frequency-domain analysis without the Hamming window and time-domain analysis. There was no significant difference in dMMGFD (EMGFD) vs. dMMGTD (EMGTD).

<table>
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<tr>
<th></th>
<th>Frequency-domain analysis without Hamming window</th>
<th>Time-domain analysis</th>
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<tbody>
<tr>
<td></td>
<td>dMMGFD [mm$^2$] EMGFD [mV$^2$] *10$^5$</td>
<td>dMMGTD [mm$^2$] EMGTD [mV$^2$] *10$^5$</td>
</tr>
<tr>
<td>51 W</td>
<td>285.4 ± 146.0 43.8 ± 23.6</td>
<td>283.9 ± 145.6 43.8 ± 23.6</td>
</tr>
<tr>
<td>68 W</td>
<td>342.4 ± 176.3 65.7 ± 37.3</td>
<td>339.6 ± 174.8 65.8 ± 37.3</td>
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<tr>
<td>80 W</td>
<td>431.6 ± 216.3 100 ± 48.3</td>
<td>427.8 ± 213.3 100 ± 48.3</td>
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<tr>
<td>99 W</td>
<td>511.1 ± 276.6 144 ± 61.0</td>
<td>507.2 ± 272.8 144 ± 61.0</td>
</tr>
<tr>
<td>108 W</td>
<td>597.0 ± 323.6 201 ± 80.7</td>
<td>591 ± 319.2 201 ± 80.6</td>
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</table>
sary to examine measures such as setting a longer analysis cycle according to the pedaling cycle and smoothing using moving average.

### 4.3 Limitation and future direction

Muscle strength (MMG output) affects the joint angle and its viscoelasticity. It should be noted that the proposed analysis method presents evaluation of muscle contraction of the whole exercise during pedaling on a recumbent bicycle, without considering the influence. Moreover, this study focused on cyclic exercise of the lower limbs using a recumbent bicycle. At the present stage, muscle contraction evaluation using the proposed analysis can only investigate periodic exercise. As a next step, further study is under way to adapt this analysis method for isometric contraction and various exercises.

Recently, various biological signals such as heart rate have been measured with a wearable device, and exercise intensity and physical activity can be monitored conveniently [29]. Moreover, EMG biofeedback therapy has been reported to promote the effect of rehabilitation, and is currently applied in various fields [30]. We believe that real-time monitoring of muscle functions using the MMG/EMG hybrid transducer system has the above-mentioned convenience and reactivity, and can provide some information of the muscle to the user. If this analysis is established, it is possible to measure the state of the contribution of multiple muscles and the temporal changes of local muscle fatigue during dynamic exercise without missing even slight change. It will be a practical tool as an indicator of rehabilitation effects and muscle strengthening exercises. Evaluation of muscle contraction by time-domain analysis not only reduces the computational cost but may also be the only technique to evaluate muscle functions in detail from both dMMG and EMG in real-time.

### 5. Conclusion

The dMMG and EMG measured using the MMG/EMG hybrid transducer system during recumbent bicycle pedaling were analyzed, and evaluation of muscle contraction during dynamic exercise was demonstrated. The $dMMG_{TD}$ and $EMG_{TD}$ calculated in time-domain analysis reflect the muscle function in dynamic exercise. Because $dMMG_{TD}$ and $EMG_{TD}$ increases with load increase during prolonged pedaling, a simplified analytical method proposed in this study may be suitable for real-time monitoring of muscle contraction during exercise. In addition to being simple and having a low computational cost, analyses of dMMG and EMG using time-domain analysis provide various information of muscle function during dynamic exercise.

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### Conflicts of interest

The authors have no conflicts of interest.

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