Novel Mechanomyogram/electromyogram Hybrid Transducer Measurements Reflect Muscle Strength during Dynamic Exercise — Pedaling of Recumbent Bicycle —

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Abstract Simultaneous measurements of mechanomyogram (MMG) and electromyogram (EMG) may be useful for accurate evaluation of skeletal muscle contraction. However, unlike the EMG, the MMG is rarely used in clinical tests. As the target muscle has to be fixed during conventional MMG measurements, it is not possible to measure MMG during dynamic exercises such as sports and rehabilitation. To solve these problems, the authors developed an MMG (displacement-MMG)/EMG hybrid transducer system that allows simultaneous MMG and EMG measurements. Furthermore, we also developed an analysis method that is able to evaluate muscle contraction using the power spectra of each signal. The measurement system and the analysis method were applied to recumbent bicycle pedaling, during which work rate was increased incrementally. The results showed that this transducer system provided MMG/EMG measurements stably during dynamic exercise. When the work rate of the bicycle pedaling increased; that is, when the dynamic muscle strength increased, the sum of the power spectra of the MMG/EMG also increased. The MMG/EMG hybrid transducer system and the analysis method were useful for evaluating muscle strength during dynamic exercise.

Keywords: mechanomyogram (MMG), electromyogram (EMG), displacement-MMG, recumbent bicycle.

Adv Biomed Eng. 7: pp. 47–54, 2018.

1. Introduction

The evaluation of muscle contraction is necessary in various situations such as research on muscle physiology, clinical evaluation of muscular diseases, and evaluation of training and muscle fatigue in sports science and rehabilitation. The mechanomyogram (MMG), which can quantitatively and noninvasively evaluate muscle contraction, has been studied previously [1–7]. When a sensor such as an accelerometer is placed on the skin surface, the MMG generally records the micro-vibrations that occur during muscle contraction [4, 5]. The MMG is generally accepted to reflect muscle mechanical activity [1, 7]. Since the MMG and electromyogram (EMG) have an input–output relation (related to the electromechanical coupling efficiency) in the process of muscle contraction, simultaneous measurements of the MMG and EMG is considered useful for accurate evaluation of muscle contraction [8–10]. The muscle contraction state cannot be evaluated using only EMG measurements. Despite the demands from various fields for quantitative evaluation of muscle contraction, the MMG is not widely used, and is currently used predominantly for research purposes. One reason is that the conventional MMG transducers [11–16] have difficulties making measurements during body movements of subjects. Therefore, the MMG is generally evaluated during isometric muscle contraction.

Based on this background, we developed a prototype MMG/EMG hybrid transducer [17] that can simultaneously measure the MMG and EMG even during dynamic exercise. The development concept for this transducer was that anyone could easily measure the MMG and EMG anywhere. We assumed that this transducer would allow MMG measurements in various fields such as clinical tests, sports, and rehabilitation.

In this study, we developed a novel MMG/EMG hybrid transducer system by improving the transducer to actually apply to various fields from the research stage. As an example of application of the MMG/EMG hybrid transducer system during dynamic exercise, we conducted simultaneous measurements of MMG and EMG during recumbent bicycle pedaling to evaluate the quadr...
riceps muscle of healthy subjects. In addition, we developed an analytical method for evaluating the MMG during dynamic exercise, and examined whether it can be applied to evaluation of muscle strength.

2. Novel MMG/EMG Hybrid Transducer System and Analysis Method

2.1 MMG/EMG hybrid transducer system

Figure 1A shows the improved MMG/EMG hybrid transducer that can simultaneously measure both MMG and EMG. This transducer measured $47 \times 34 \times 24\ mm$ and weighed 34 g. The characteristic MMG sensor of this transducer used a photo reflector (TCRT1000, Vishay Intertechnology, Inc., USA). The photo reflector was designed to be 3 mm above the skin surface. The skin variation according to the change in cross-sectional area was recorded as the displacement-MMG (dMMG). The dMMG measured by this system was calculated in advance from the calibrated distance–voltage characteristics which was approximated by a cubic curve, and the dynamic range was 1–8 mm. The maximum quantification error was $\pm 4\ \mu\m$ in the 12-bit A/D conversion. Improvements from the previous MMG/EMG hybrid transducer were as follows: (1) the EMG was measured by attaching disposable electrodes to the bottom of the transducer; (2) the electronic circuit performing the measurement was packed inside the transducer (before the analog-to-digital conversion, the EMG signal was amplified by a factor of 160 and filtered at 5.3–500 Hz.), and an SD card was used for data storage; (3) a personal computer or portable device controlled the transducer, and the transducer and the computer terminal communicated via Bluetooth® (ver. 4.0 or later); (4) in order to affix the transducer to the skin, we created a dedicated belt that could be easily wrapped around the leg or arm, depending on the target muscles (Fig. 1B); (5) we developed measurement and control software that can collectively operate up to five MMG/EMG hybrid transducers and display up to 10 windows of real-time dMMG and EMG output (Fig. 1C). The setting items were the measurement time and the sampling time. The total recording time was the time from start to end of the measurement and could be set from 1 to 3600 s. The sampling time was the inverse of the sampling frequency and could be set from 1 to 1000 ms. The voltage data were converted from analog to 12-bit digital, and temporarily stored in binary format on an SD card. Finally, the data were converted to mm (dMMG), mV (EMG) using the software and saved on a personal computer. From the above, we produced a comprehensive MMG/EMG hybrid transducer system, including the hardware and software related to the dMMG and EMG measurements.

2.2 Analysis method for evaluation of muscle contraction during dynamic exercise

We developed a novel analysis method for the evaluation of dynamic muscle contraction using the dMMG and EMG. Figure 2 shows the typical original waveforms and the spectrum waveforms of the dMMG and EMG during recumbent bicycle pedaling. The detailed analysis method for the dMMG during dynamic exercise was as follows. First, the objects to be analyzed were three pedaling waveforms in 10 s, and the average value was subtracted from the measured dMMG waveform to remove the direct-current (DC) component. Next, the target waveform was processed with a Hamming window and a discrete Fourier transform. Finally, the total power (area value) of the power spectrum below 100 Hz was calculated as a parameter representing the dynamic muscle strength (dMMG$_{FT}$). The frequency component of the MMG has been reported to be below 100 Hz [18–20]. The EMG analysis followed the same method as for dMMG. The waveforms to be analyzed were synchronized with the time phases targeted by the dMMG. The EMG was evaluated for total power (EMG$_{FT}$) by integrating the power spectrum below 500 Hz.
Normalization of dMMG FT was based on the averaged value of dMMG FT during passive pedaling (described later), and normalization of EMG FT was based on the maximum value of the EMG FT.

3. Methods

Four healthy adult male volunteers (age, 25.5 ± 7.0 years) without orthopedic disease participated in this study.

The MMG/EMG hybrid transducer was attached to the vastus medialis of the right (dominant) foot at the center of the muscle (Fig. 3A). The transducer was gently fixed to the thigh using a dedicated belt. To ensure stable electrode contact, the skin was prepared by rubbing the surface with electrode gel.

The subject was seated on a recumbent bicycle (C545R, SportsArt, USA) with a moderate natural sitting posture and both feet fixed to the pedals (Fig. 3B). The subject was instructed not to move the upper half of the body or the ankles. The dMMG and EMG signals were sampled at 1000 Hz. The dMMG and EMG data were stored on an SD card of the transducer that communicated with a personal computer via Bluetooth®.

After completing the setup, the subject pedaled at 60 rpm, aided by a metronome. After the subject’s pedaling velocity was confirmed to be constant, the dMMG and EMG measurements were performed for 10 s. The pedaling work rate was increased incrementally as follows: 51, 68, 80, 99, and 108 W. We also measured dMMG and EMG during “passive pedaling” (two of the authors rotated the pedals while the subject did not exert muscle strength). Each pedaling load was measured four times. Sufficient rest time was provided between experiments. The resulting dMMG and EMG were analyzed according to the procedures of the analysis method.

This study was conducted according to the principles of the Declaration of Helsinki and with ethical approval from the Okayama University Ethics Committee (approval number 1703-013). The subjects received sufficient explanations about the experiment and participated in the experiment after agreement.

4. Results

Typical raw waveforms of the dMMG and EMG are shown in Fig. 4. The dMMG and EMG recorded stable waveforms, even during dynamic exercise. The EMG exhibited a flat waveform during passive pedaling, and the amplitude of the waveform increased as the work rate increased. The dMMG showed periodic waveforms during all pedaling sessions, including passive pedaling. The amplitude of the waveforms increased in the order of passive pedaling, 68 W, and 108 W. A slight increase was observed between 68 W and 108 W.

The relationship between work rate and dMMG FT, EMG FT, normalized dMMG FT, and normalized EMG FT are shown in Figs. 5 and 6. The dMMG FT and EMG FT continued to increase with increasing work rate, showing that the dMMG FT and EMG FT increased as the muscle strength increased. The dMMG FT included the involuntary muscle movement during pedaling by passive joint movement (passive pedaling). The normalized dMMG FT, an indicator of muscle strength, was calculated based on the dMMG FT generated by passive pedaling. The net muscle strength was obtained by subtracting “1.0” (the base value) from the normalized dMMG FT, as shown in Fig. 6. Since the normalized EMG FT was calculated us-
ing the maximum value as reference, it had the same meaning as before normalization. In addition, the normalized dMMGFT and normalized EMGFT were linearly approximated and showed a strong correlation with the work rate.

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Fig. 4 Typical 10-second dMMG and EMG raw waveforms for (a) passive pedaling and work rates of (b) 68 W and (c) 108 W.

Fig. 5 Relationship between work rate and (a) EMGFT (open circles), (b) dMMGFT (closed triangles). The dMMGFT graph shows the dMMGFT of passive pedaling without relation to work rate. All quantitative data are means ± SD.

Fig. 6 Relationship between work rate and normalized EMGFT and normalized dMMGFT. The left vertical axis indicates the value obtained by subtracting “1.0” from the normalized dMMGFT. The solid line (normalized EMGFT) and dotted line (normalized dMMGFT) are linear approximations.

The MMG was expected to directly reflect the muscle strength [2]. The EMG in healthy people has been used as one of several muscle strength evaluations [21]. The normalized dMMGFT and normalized EMGFT had a positive correlation (Fig. 7). Subjects 1 and 2, in particular, showed a strong correlation. This correlation indicates that the normalized dMMGFT reflects the muscle strength. In addition, the slope of the regression line may be interpreted as the electromechanical coupling efficiency of the muscle contraction process [8–10].
5. Discussion

5.1 MMG/EMG hybrid transducer system and analysis method

Several examples of MMG measurement of non-isometric contractions have been reported using conventional transducers. The contact sensor (HP-21050A, Hewlett-Packard, USA) captured the displacement of muscle movement. However, installation of the sensor was complicated, and the transducer itself was heavy, which seemed to be disadvantageous in clinical and sports settings [22, 23]. Meanwhile, the accelerometer captured the acceleration of the muscle movement. However, this method was limited to quasi-static movements, and was affected by motion artifact during dynamic exercise [24, 25]. The MMG/EMG hybrid transducer that we developed captured the displacement of muscle even during dynamic exercise, was easy to install, and had wireless communication. Therefore, the novel system can be used to evaluate muscle contraction in various fields.

The dMMG recorded by our transducer was not affected by noise or motion artifacts, unlike the accelerometer [12], and stable waveforms were acquired, as shown in Fig. 4. The dMMG indicates morphological changes of the muscle; that is, the changes in physiological cross-sectional area. Muscle displacement in the vertical direction is derived from the changes in muscle fibers accompanying muscle contraction [1, 26]. The dMMG detected the recruitment of muscle fibers, and seemed to indicate the muscle contraction state [27]. However, the change in dMMG was very small (several hundred micrometers), as shown in Fig. 4, which was anticipated to be difficult to handle as part of the practical evaluation of muscle contraction in various fields. Although acceleration MMGs are usually measured with acceleration sensors (accelerometer), we attempted to calculate the acceleration MMG from the second order differential of dMMG during dynamic exercise. However, this acceleration MMG was significantly affected by the change in rotation speed of pedaling of the recumbent bicycle. When the pedaling speed is slightly different, the resulting muscle force may be incorrect.

The dMMG_FT obtained by the novel analysis method is the sum of the vibration components in the uniaxial direction of muscle contraction, and indicates the output energy of the muscle. However, it should be noted that the total power determined by this method also includes changes in the physiological muscle cross-sectional area due to passive joint movement. Accordingly, the muscle strength during dynamic exercise can be determined by using the total power of the passive joint movement as reference to generate normalized dMMG_FT.

5.2 Evaluation of MMG and EMG during recumbent bicycle pedaling

Since the vastus medialis is a muscle that exerts strength or increases its cross-sectional area during knee extension, the dMMG and EMG amplitudes increased when stepping down on the pedal and decreased when pulling up on the pedal. During passive pedaling, the EMG was non-observable while the dMMG appeared as periodic waveforms, due to the involuntary physiological muscle cross-sectional area changes accompanying passive extension and flexion of the lower limb. In addition, increases in the physiological muscle cross-sectional area due to muscle contraction were reflected as increases in the amplitude of the dMMG. In other words, the dMMG during voluntary dynamic exercise is a signal obtained by superimposing the muscle contraction component on the passive pedaling dMMG.

In order to maintain pedaling at a constant velocity, the muscle must exhibit action potential and mechanical muscle strength corresponding to work rates. In this study, dMMG_FT and EMG_FT outputs necessary for pedaling were observed, as shown in Figs. 5 and 6. Several studies of the MMG amplitude in cycle ergometry have been reported [28–31]. In these studies, the MMG amplitude increased during incremental cycle ergometry. In particular, Shinohara et al. [28] and Perry et al. [29] reported that in the quadriceps muscle, the MMG ampi-
tude increased linearly with the power output, and the EMG amplitude increased linearly or curvilinearly. It appears that these previous studies support the results of the current study.

We showed that the normalized dMMG\textsubscript{FT} correlated positively with the normalized EMG\textsubscript{FT}. We consider that the study results are reasonable and proper because the study was conducted in healthy subjects [32]. Moreover, the differences in correlation between subjects (subjects 1 and 2 versus subjects 3 and 4) may indicate the presence or absence of reserve power of muscular strength in the pedaling load. Barry et al. [8] reported the dissociation of electromechanical coupling efficiency between pediatric muscular dystrophy patients and healthy subjects. It is important to note the slope of the regression line. This slope may represent the contracted state of each muscle during dynamic exercise. Observing the slopes of regression lines of multiple muscles may elucidate differences between left and right muscles, differences in the contribution rate of muscles when changing the exercise method, and local muscle fatigue during dynamic exercises such as in sports and rehabilitation. However, because this study had few subjects, this problem needs further investigations and is still open for discussion.

Seki el al. [33] developed a cycling wheelchair (CWC) that could move around freely using one-handed steering and pedaling, and reported the EMG appearance on the affected side of a hemiplegia patient performing rehabilitation using a CWC. We believe that the system developed herein can be used in most dynamic rehabilitation cases including the CWC. Because it can evaluate the rehabilitation effects using both MMG and EMG, a new indicator of patient’s convalescent status can be obtained.

This system and the analysis method have several limitations. First, as evident from the size of the transducer and its attachment method, measurements are limited to relatively large muscles. Therefore, transducer compactification is required. Second, in cases where passive movement is difficult to measure (such as exercises involving complex movements or exercises for which other people cannot reproduce the body movements), it will be difficult to extract the muscle strength using the analysis method presented in this study.

In the current study, we developed the MMG/EMG hybrid transducer system capable of simultaneous measurements of dMMG and EMG, and proposed an analysis method for the evaluation of muscle contraction during dynamic exercise. Applying this system to recumbent bicycle pedaling, the dMMG and EMG were measured simultaneously. We demonstrated that (1) the dMMG and EMG consisted of stable waveforms during dynamic exercise; (2) as the pedaling work rate increased; that is, as the dynamic muscle strength increased, the dMMG\textsubscript{FT} and EMG\textsubscript{FT} also increased; (3) the normalized dMMG\textsubscript{FT} was an indicator of muscle strength during dynamic exercise; and (4) muscle electromechanical coupling efficiency was indicated by the correlation between normalized dMMG\textsubscript{FT} and normalized EMG\textsubscript{FT}. Our study thus demonstrated that the novel MMG/EMG hybrid transducer reflects muscle strength during dynamic exercise.

6. Conclusion

The MMG and EMG obtained using the proposed system and analysis methods provide evidence that muscle strength can be evaluated even during dynamic exercise. These results suggest that the MMG/EMG hybrid transducer system with excellent versatility may be a powerful tool for the evaluation of muscle contraction during dynamic exercise.

Acknowledgement

This research was partially supported by Okayama Prefecture in 2016 and a Grant-in-aids for Scientific Research (17K01360) from Japan Society for the Promotion of Science.

Conflicts of Interest

The authors have no conflict of interest with any companies or organizations based on the definition of Japanese Society for Medical and Biological Engineering.

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