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EMG-based Detection of Muscle Fatigue during Low-Level Isometric Contraction by Recurrence Quantification Analysis and Monopolar Configuration

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Abstract— **The center frequency (CF) of the power spectral density of a bipolar-configured surface electromyogram is typically used as an index of muscle fatigue. However, this index may be inadequate for measuring wave slowing due to muscle fatigue during low-level contractions. A previous study in which strong muscle fatigue was mimicked by compressing the proximal region of the forearm during isometric contractions showed that the differences in the degree of fatigue under compression and non-compression conditions were undetectable. The purpose of this study was to improve detection sensitivity of surface EMG variation caused by muscle fatigue using two approaches. The first approach employed recurrence quantification analysis (RQA) instead of traditional frequency analysis (FA) to compute the muscle fatigue index. The second approach employed a monopolar configuration for measuring surface EMG. We measured the surface EMG signal by using monopolar and bipolar configurations simultaneously during low-level isometric contractions under blood flow-restricted (BFR) and unrestricted (CON) conditions, and then compared and evaluated the detected differences in muscle fatigue. The results showed that the effect of BFR was better detected by RQA than by FA, and that the fatigability change was larger in the monopolar configuration than in the bipolar configuration.**

I. Introduction

Exercise therapy, dietary therapy, and medication therapy are currently known as effective medical remedies against lifestyle-related diseases. Among them, exercise therapy is widely practiced because it is helpful in preventing diseases as well as leading to cures for diseases [1]. Isometric exercise is one exercise therapy capable of being carried out safely and conveniently, and is primarily used for patients with rheumatoid arthritis. In isometric exercise, the contractile force of the muscle generates pressure by reducing the cross-sectional area of the muscle because the muscle length does not change. This, in turn, applies pressure to the blood vessel traveling within the muscle, increasing the peripheral resistance of the vascular system. As a result, blood pressure may rise significantly and there is a possibility of strong muscle fatigue. In the case of isometric exercise that targets the elderly, there is a particular need to pay close attention to changes in peripheral hemodynamics and muscle fatigue [2].

As an indicator of peripheral circulation, muscle oxygen dynamics using near-infrared spectroscopy (NIRS) are used. To detect changes in muscle fatigue, surface electromyogram (SEMG) is typically used. As a quantitative assessment of muscle fatigue using SEMG, the rate of decline of the center frequency (CF) is generally used. The CF can be calculated by the power spectral density (PSD) of SEMG, which is estimated using a fast Fourier transform (FFT) with a window function [3].

A bipolar configuration (BPC) is generally used for measuring SEMG. With bipolar configuration, a pair of electrodes is stuck on a specific active body part and the potential difference between both electrodes is measured. However, even if contraction during low-intensity exercise is performed until near complete exhaustion, the change in the SEMG accompanying the fatigue may be undetectable by bipolar configuration [4]. Additionally, in research where isometric movement was made by raising blood pressure compulsorily by placing pressure on the base of the extremity, SEMG obtained by bipolar configuration did not result in a significant difference between the pressure conditions [5], [6].

One solution is to record the EMG by monopolar configuration (MPC) instead of bipolar configuration. With monopolar configuration, one electrode is stuck on an active body part and the other is stuck on an electrically inactive place, such as a ground electrode, and the potential difference between both electrodes is detected. Because monopolar configuration has a wide derivation range and flat frequency characteristic relative to bipolar configuration, there is a possibility to detect changes in SEMG due to fatigue. The second approach employs recurrence quantification analysis (RQA), a nonlinear analysis technique, instead of frequency analysis (FA). The technique is particularly attractive for measuring biological signals for at least three reasons: RQA does not require large stationary data sets; RQA makes no assumptions as to the statistical nature of the input data; and RQA can resolve time correlations within otherwise random-looking signals [7]. It was reported that the percentage of determinism (%DET) calculated using RQA increases with the progression of muscle fatigue [8]; The %DET is a quantitative evaluation index of RQA. Because it is believed that this evaluation index detects muscle fatigue from a different perspective with FA, RQA has the possibility for being an effective approach for evaluating muscle fatigue.

The purpose of this study is two-fold: to detect EMG fatigue changes during low-level isometric contraction, which the abovementioned conventional method cannot observe, and to detect the difference in the degree of fatigue under compression and non-compression conditions. Strong muscle fatigue, which may occur during isometric exercise owing to an increase in the peripheral resistance of the vascular system,

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is mimicked by compressing the proximal region of the forearm during isometric contractions. The occurrence of strong muscle fatigue is confirmed by measuring muscle oxygen dynamics using NIRS.

II. Experimental Methods

The subjects in this study were eight healthy male adults, each 21 years old, all of whom were right-handed. Each of them was informed of the details and risks involved of the experiment in advance and gave written consent for voluntary participation in the experiment. Each subject was seated comfortably with his dominant upper arm fixed perpendicular to his body trunk with his forearm supinated and his elbow extended. The duration of the exercise was set at 8 min. Preliminary experiments confirmed that the exercise intensity in the experiment corresponds to about 10 % of the maximum voluntary contraction.

Surface EMG signals were recorded with monopolar and bipolar configurations during a low-level isometric muscle contraction under blood flow-restricted (BFR) and unrestricted (CON) conditions. The muscle measured was the long head of the biceps brachii muscle, which functions as a supinator muscle in the forearm. Muscle oxygen metabolism was also measured simultaneously.

Under the BFR condition, forearm blood flow was restricted by placing a pneumatic cuff (aneroid sphygmomanometer, Q9917, YAMASU) on the upper arm at a pressure of 200 mmHg. The restriction was maintained for 5 min. Even after the restriction was discontinued, the exercise was continued for another 3 min.

Muscle oxygen metabolism was measured using an infrared oxygen monitoring device (NIRO-200NX, Hamamatsu Photonics K.K.). Irradiation and detection probes were placed perpendicularly to the muscle fibers over the muscle belly mid-portion. The distance between the probes was set to 40 mm, and the sampling frequency was set to 1 Hz. We measured the oxygenated hemoglobin concentration variation (ΔO2Hb μmol*cm), deoxygenated hemoglobin concentration variation (ΔHHb μmol*cm), tissue oxygenation index (ΔTOI %), and normalized tissue hemoglobin index (nTHI).

We measured the surface EMG signal by using the monopolar and bipolar configurations simultaneously. Active electrodes (material: gold, shape: disc, diameter: 14 mm, AP-C300, DIGITEX LAB) were used as recording, ground, and reference electrodes. In the monopolar configuration, the recording, ground, and reference electrodes were placed over the muscle belly mid-portion of the long head of the biceps brachii muscle, the wrist, and the elbow, respectively. In the bipolar configuration, the recording electrodes were placed over the same muscle parallel to the longitudinal axis of the muscle fiber and were fixed so as not to sandwich the neuromuscular junction. The electrodes in bipolar configuration had a center-to-center spacing of 20 mm. The surface EMG signals recorded by the recording electrodes were sampled at 1000 Hz using a built-in A/D converter in a biological signal recording apparatus (PolymateII AP216, DIGITEX LAB). To eliminate noise in the surface EMG signal after A/D conversion, the signal was filtered between 10 and 500 Hz and also between 49 and 51 Hz.

III. Data Analysis

A. Muscle Oxygen Metabolism

The muscle oxygen metabolism data from each 8 min contraction were segmented nearly equally into 56 noncontiguous epochs. Each epoch comprised 8 points (8 s) and the average values were calculated. Next, for each condition, the average values of corresponding epochs for all subject data were calculated.

B. Frequency Analysis (FA)

The surface EMG data from each 8 min contraction was segmented nearly equally into 56 noncontiguous epochs. Each epoch comprised 8192 points (8.192 s). The PSD $P(f)$ was estimated from each epoch using a Hanning window and FFT, and the CF was computed according to the following formula:

$$\int_0^{\mathrm{CF}} P(f)\,\mathrm{d}f = \frac{1}{2}\int_0^{\frac{\mathrm{f_s}}{2}} P(f)\,\mathrm{d}f$$

where f_s is the sampling frequency. Next, for each 8 min contraction, the values of CF were normalized against the starting value, which was assumed to be 100 %. Finally, average values of corresponding epochs of all subject data were calculated for each condition. Although both the mean frequency and CF have been used as indices of the EMG power spectrum, the CF is less affected by noise. The value of the CF decreases with the progression of muscle fatigue.

C. Recurrence Quantification Analysis (RQA)

RQA is an effective method for detecting the deterministic structure and complexity of an underlying dynamical process of a time series. The analytical procedure is summarized as reconstruction of a phase space, construction of a recurrence plot, and extraction of quantitative indicators from the recurrence plot.

Given the surface EMG signal samples $x(i)$, the phase space vector $X(i)$ can be constructed as follows:

$$X(i) = (x(i), x(i+\tau), x(i+2\tau), \cdots\ x(i+(m-1)\tau)$$

where τ is the time delay and m is the embedding dimension. The recurrence plot is essentially a 2-dimensional plot obtained by computing all the distances between phase space vectors $X(i)$ and $X(j)$. Once the threshold distance ϵ is defined, a binary plot can be constructed, in which the point (i, j) is represented by a black dot if the distance between $X(i)$ and $X(j)$ is smaller than ϵ. In this case, the point is recurrent. If the distance between $X(i)$ and $X(j)$ is larger than ϵ, the point (i, j) is assigned a white dot. The percentage of recurrence (%REC) and the percentage of determinism (%DET) were employed as RQA indicators; The %REC is a measure of the density of recurrent points in the recurrence plot, and the %DET is the ratio of recurrent points forming diagonals of length l_{min} to all recurrent points and is a measure of the predictability of the system.

In this study, the %REC was used to evaluate the adequacy of the recurrence plots and the %DET was used as a muscle fatigue indicator. The value of the %DET increased with progression of muscle fatigue. The Cross Recurrence Plot Toolbox 5.16 for Matlab [9], [10] was used to perform RQA.

The time delay τ and the embedding dimension m were estimated using mutual information and a false nearest-neighbors method, respectively. Based on [11] and the estimated value of the %REC, the threshold distance ϵ was set to 10 % of the maximal phase space diameter. The L_2-norm (Euclidean norm) was used for computations of distance. The minimal length of the diagonal structure l_{min} was set to 2.

D. Statistical Analysis

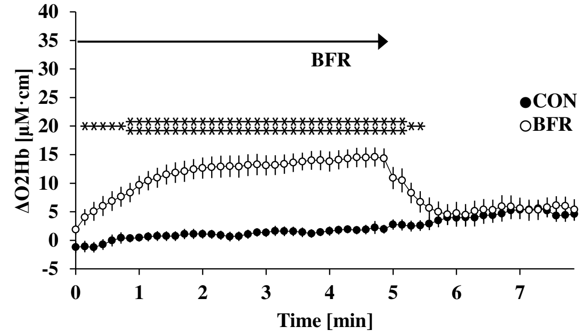
Values are presented as mean $\pm$SE. Prior to the significance test, the normality of the data was checked with the two-sided Jarque-Bera test with a significance level of 0.05 or 0.01. The normality criteria were met; therefore, the two-sided, one-sample t-test (parametric method) with significance levels of 0.1, 0.05, and 0.01 was employed. All statistical analyses were performed with dedicated software (Ekuseru-Toukei 2010, Social Survey Research Information). The targets for the comparison of significance testing are the data in a simultaneous series between each experimental condition. With respect to the CF and %DET, data that varied by 20 % from the start of the exercise were chosen as the target data.

IV. RESULTS

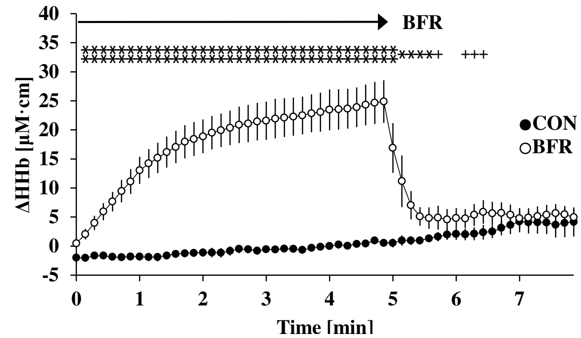
Fig. 1 shows ΔO_2Hb, ΔHHb, ΔTOI, and nTHI under the BFR and CON conditions. As shown in Fig. 1(a), the ΔO_2Hb under the BFR condition is above that under the CON condition from the start of the movement to 5 min 30 s ($P < 0.05$ or $P < 0.01$). As shown in Fig. 1(b), the ΔHHb under the BFR condition is above that under the CON condition from the start of the movement to 5 min 30 s ($P < 0.05$ or $P < 0.01$). Also, it shows a high tendency from 6 min to 6 min 30 s ($P < 0.1$). As shown in Fig. 1(c), the ΔTOI under the BFR condition shows a low tendency from 3 min to depressurization time ($P < 0.1$). Fig. 1(d) shows that the nTHI under the BFR condition is above that under the CON condition from 30 s to depressurization time ($P < 0.05$ or $P < 0.01$). Also, before or after the period, it shows a high tendency ($P < 0.1$).

Fig. 2 shows the CF values between each condition. As shown in Fig. 2(a), although the CF under the BFR-BPC condition shows a lower value relative to that under the CON-BPC condition, a significant difference between both conditions was not observed. With respect to the CF under the CON-BPC condition, there is a significant difference 6 min 30 s from the start of the exercise ($P < 0.01$), whereas with respect to the CF under the BFR-BPC condition, there is a significant difference 5 min from the start of the exercise ($P < 0.05$ or $P < 0.01$). As shown in Fig. 2(b), the CF under the CON-MPC condition is below that under the CON-BPC condition from 30 s to 7 min almost continuously ($P < 0.05$ or $P < 0.01$). Also, it shows a low tendency from 7 min to 7 min 30 s ($P < 0.1$). For the CF under the CON-MPC condition, there is a significant difference 2 min from the start of exercise ($P < 0.05$ or $P < 0.01$).

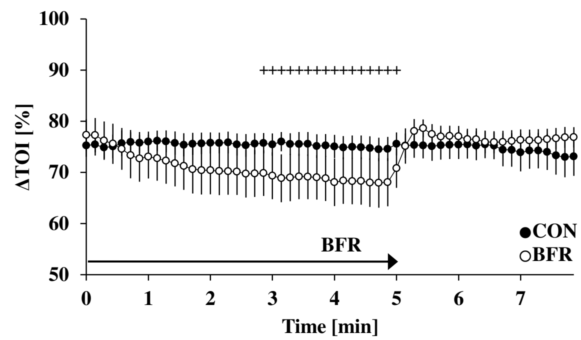
Fig. 3 shows the %DET values between each condition. As shown in Fig. 3(a), the %DET under the BFR-BPC condition has a significant difference and a tendency difference relative to the CON-BPC condition around 1 min and from 3 min 30 s to 6 min 30 s almost continuously ($P < 0.05$ or $P < 0.1$).



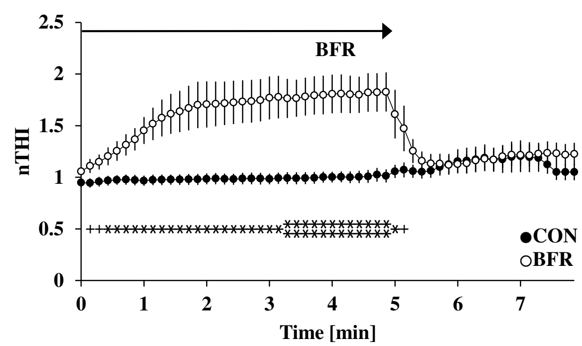
(a) ΔO_2Hb



(b) ΔHHb



(c) ΔTOI



(d) nTHI

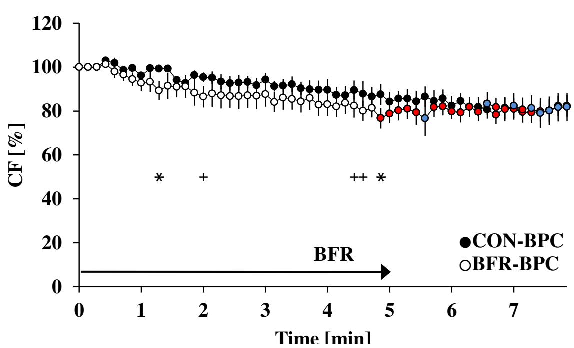
Figure 1. Changes in ΔO_2Hb, ΔHHb, ΔTOI, and nTHI under BFR and CON conditions. Values are mean $\pm$SE (standard error) of 8 samples. The symbol * expresses the significant difference at the 5% significance level, ** expresses the significant difference at the 1% significance level, and + expresses the tendency difference at the 10% significance level.

Regarding the %DET under the CON-BPC condition, there is no significant difference from the start of the exercise, whereas with there is a significant difference and a tendency difference 2 min 30 s after the start of the exercise ($P < 0.05$ or $P < 0.01$ or $P < 0.1$) for the %DET under the BFR-BPC condition. As shown in Fig. 3(b), the %DET under the CON-MPC condition has a significant difference and a tendency difference relative to the CON-BPC condition from 30 s to 4 min and from 5 min 30 s almost continuously ($P < 0.05$ or $P < 0.01$ or $P < 0.1$). And, for the %DET under the CON-MPC condition, there is a significant difference and a tendency difference 2 min after the start of exercise almost continuously ($P < 0.05$ or $P < 0.01$ or $P < 0.1$).

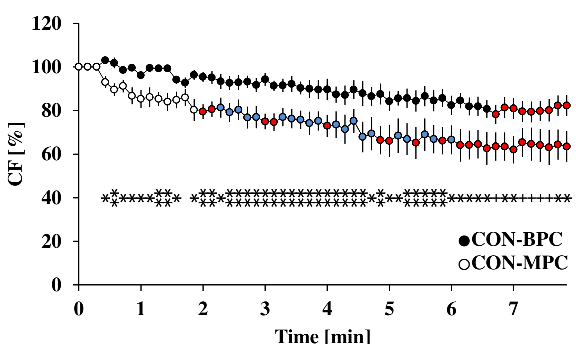
V. Discussion

As indicated in Fig. 1, under the CON condition, ΔO2Hb and ΔHHb increased slightly and gradually as the exercise continued and ΔTOI and nTHI were almost constant. On the other hand, under the BFR condition, ΔO2Hb and ΔHHb showed a significant increase from the start time of movement until depressurization time, and the increased amount of ΔO2Hb was larger than that of ΔHHb. Additionally, ΔTOI decreased and nTHI increased.

In general for low-level contractions and because the internal pressure of the muscle was low and intra-muscle blood flow was maintained, it is believed that the oxygen demand of active muscles was fulfilled [12]. Also in this experiment, under the CON condition, the variation in the amounts of ΔO2Hb and ΔHHb was very small and ΔTOI was almost constant, showing that the balance between supply and consumption of oxygen in the muscle was maintained. On the other hand, under the BFR condition, the increased amount of ΔHHb was larger than that of ΔO2Hb, and ΔTOI decreased, showing that the balance between oxygen supply and consumption in the muscle had been lost. It is suggested that the muscle had fallen into the hypoxic condition. Additionally, the increased nTHI showed retention of intra-muscular blood flow caused by the increase in peripheral vascular resistance by pressurization load, suggesting that the muscle caused intravenous congestion. The hypoxic condition and intravenous congestion cause accumulation of anoxic metabolic products such as lactic acid, hydrogen ions, and adenosine, which inhibit energy production needed for muscle activity and loss in muscle strength. To compensate for loss in muscle strength, it is inferred that more motor units, including not only slow-twitch muscle fibers but also fast-twitch muscle fibers, are recruited.

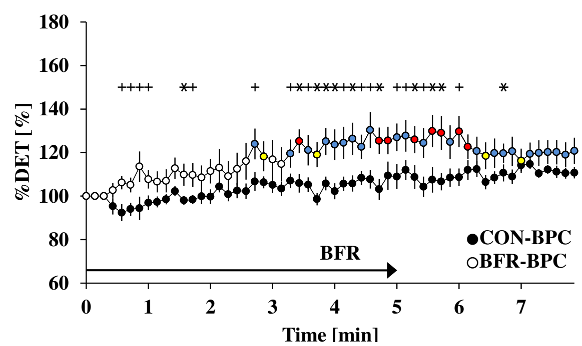


(a) CON-BPC and BFR-BPC conditions

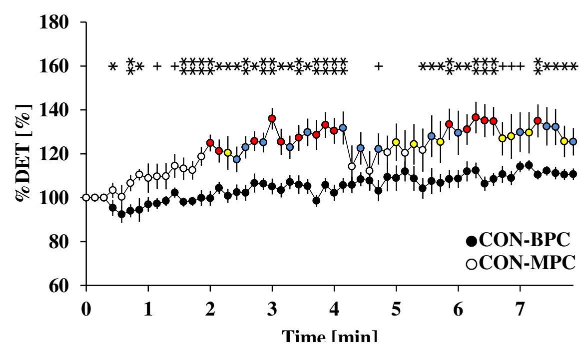


(b) CON-BPC and CON-MPC conditions

Figure 2. Changes in CF between each condition. The CF is normalized to its initial value. Values are mean ±SE (standard error) of 8 samples. The symbol * expresses the significant difference at the 5% significance level, ** expresses the significant difference at the 1% significance level, and + expresses the tendency difference at the 10% significance level. The colored markers are where the significant difference or the tendency difference was observed compared with the time of movement start. The target data occur after the CF was reduced by 20 % from the time of movement start. The blue marker expresses the significant difference at the 5% significance level, the red marker expresses the significant difference at the 1% significance level, and the yellow marker expresses the tendency difference at the 10% significance level.



(a) CON-BPC and BFR-BPC condition



(b) CON-BPC and CON-MPC condition

Figure 3. Changes in %DET between each condition. %DET is normalized to its initial value. Values are mean ±SE (standard error) of 8 samples. The symbol * expresses the significant difference at the 5% significance level, ** expresses the significant difference at the 1% significance level, and + expresses the tendency difference at the 10% significance level. The colored markers are where the significant difference or tendency difference was observed compared with the time of a movement start. The target data occurred after the %DET was increased by 20 % from the time of movement start. The blue marker expresses the significant difference at the 5% significance level, the red marker expresses the significant difference at the 1% significance level, and the yellow marker expresses the tendency difference at the 10% significance level.

As Fig. 2(a) illustrates, there were few significant and tendency differences between the BFR and CON conditions when using the CF as an indicator of muscle fatigue. Therefore, the CF cannot detect promotion of muscle fatigue caused by muscle blood flow restriction; similar results have been obtained in previous studies [5], [6]. On the other hand, as shown in Fig. 3(a), using the %DET as an indicator of muscle fatigue showed that there were significant and tendency differences of approximately half. This result suggests that the %DET has the potential to detect promotion of muscle fatigue by muscle blood flow restriction. Also, as indicated in Fig. 2(a) and Fig. 3(a), the %DET showed a significant difference against the start of the exercise at an early stage than the CF under the BFR condition. In this manner, the detection sensitivity of muscle fatigue by the %DET is better than that by the CF under the BFR condition.

As displayed in Fig. 2(b) and Fig. 3(b), under the CON condition, both the CF and the %DET of the MPC showed a significant change in EMG fatigue, although the significant difference in the %DET is lost around 5 min and there was instability in the transition. Also, both indicators of the MPC showed a significant difference against the start of the exercise at an early stage over the BPC indicators. From these results, it may be concluded that the MPC can detect EMG fatigue changes more clearly than the BPC.

VI. Conclusion

This study attempted to improve the detection of muscle fatigue during low-intensity exercise using RQA and MPC. Our findings suggest that RQA is superior to FA in detecting the promotion of muscle fatigue by muscle blood flow restriction, and that MPC outperforms BPC in terms of detecting changes in fatigue. A subsequent study for other muscles should be performed to confirm these findings.

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