Detection of Muscle Fatigue during Low-Level Isometric Contraction using Recurrence Quantification Analysis

K. Ito, Y. Hotta and T. Abe

Niigata Institute of Technology/Department of Information and Electronics Engineering, Kashiwazaki, Japan

Abstract—This study aimed to detect muscle fatigue during low-level isometric contraction using recurrence quantification analysis (RQA). It also examined whether the electrode configuration affects the sensitivity of detection of muscle fatigue. Five healthy subjects in their 20s participated in the experiment. They kept their dominant arm fixed parallel to the floor for 10 minutes. The surface EMG signal from the biceps brachii was recorded using bipolar and bipolar configurations. The RQA-based fatigue index was calculated as the percentage of determinism (%DET). The results can be summarized as follows. 1) %DET significantly increased with progression of fatigue. RQA is therefore capable of detecting muscle fatigue during low-level isometric contraction. 2) The %DET recorded by the bipolar configuration exhibited somewhat larger variation than that recorded by the bipolar configuration. The unipolar configuration appears to be more effective in detecting muscle fatigue by RQA. 3) %DET is more sensitive than a traditional index, median frequency (MDF), to fatigue-induced changes.

Keywords—muscle fatigue, surface EMG, recurrence quantification analysis, isometric contraction.

I. INTRODUCTION

Median frequency (MDF) of the power spectrum density (PSD), muscle fiber conduction velocity (CV), and/or average rectified value (ARV) are the typically used electromyogram (EMG) recording-based muscle fatigue indicators. MDF and CV decrease and ARV increases when muscle is fatigued [1]-[3]. During low-level contraction, however, the above variations may be small and difficult to detect.

This study used recurrence quantification analysis (RQA) [3], which has recently been used to evaluate muscle fatigue, to detect muscle fatigue during low-level muscle contraction and examined the effectiveness of this method. The percentage of determinism (%DET) parameter increases with progression of muscle fatigue. As this index is expected to detect muscle fatigue in a manner qualitatively different from that of the traditional indices, it is possible that the use of RQA can improve the detection of muscle fatigue during low-level muscle contraction.

This study also investigated whether the detection sensitivity of RQA varies depending on the electrode configuration (unipolar and bipolar configurations). In general, a bipolar (single differential) configuration is employed to measure surface EMG. This is mainly due to the ability to eliminate noise that becomes mixed in the electrode terminal in phase, such as power noise. The noise elimination is accomplished by differential amplification. However, since a bipolar configuration has frequency characteristics similar to those of high-pass filters, they attenuate the low-frequency components of EMG signals. It is possible that this effect will interfere with detection of muscle fatigue. To confirm this, a unipolar configuration, which is the simplest configuration and does not exhibit this frequency characteristic, was also used to measure the EMG signal. The unipolar configuration has a wider derivation region than the bipolar configuration, allowing it to pick up more motor units and thus making muscle fatigue easier to detect.

II. ANALYTICAL METHODS

A. Recurrence quantification analysis

RQA is an effective method for detecting the deterministic structure and complexity of the underlying dynamical process of a time series. The analytical procedure is summarized as follows: 1) reconstruction of a phase space, 2) construction of a recurrence plot, and 3) extraction of quantitative indicators from the recurrence plot [4].

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

\[
X(i) = (x(i), x(i + \tau), x(i + 2\tau), \ldots, x(i + (m-1)\tau))
\]

where \( \tau \) is the time delay and \( m \) is the embedding dimension. The recurrence plot is essentially a 2-dimensional plot obtained by computing all of the distances between the phase space vectors \( X(i) \) and \( X(j) \). Once the threshold distance \( \epsilon \) 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 \( \epsilon \). In this case, the point is recurrent. If the distance between \( X(i) \) and \( X(j) \) is larger than \( \epsilon \), the point \((i,j)\) is assigned a white dot. Percentage of recurrence (%REC) and percentage of determinism (%DET) were employed as RQA indicators [3]. %REC is a measure of the density of recurrent points in the recurrence plot.
plot, while %DET is the ratio of the recurrent points forming diagonals of length \( l_{\text{min}} \) to all recurrence points and is a measure of predictability of the system.

In this study, %REC was used to evaluate the adequacy of the recurrence plots and %DET as a muscle fatigue indicator. The value of %DET increases with progression of muscle fatigue. The Cross Recurrence Plot Toolbox 5.16 for Matlab [5], [6] was used to perform RQA.

B. Spectral analysis

The PSD \( P(f) \) of the surface EMG signal was estimated using a Hanning window and fast Fourier transform (FFT), and the median frequency (MDF) was computed according to the following formula:

\[
\int_0^{\text{MDF}} P(f) \, df = \frac{1}{2} \int_0^{f_s} P(f) \, df
\]

where \( f_s \) is the sampling frequency. Although both mean frequency (MNF) and MDF have been used as indices of the EMG power spectrum, MDF is less affected by noise. The value of MDF decreases with the progression of muscle fatigue.

III. EXPERIMENTAL METHODS

The subjects were 5 healthy male adults in their 20s. Four of them were right-handed. Each was informed of the content and risks of the experiment in advance and gave written consent for voluntary participation in the experiment. Each subject was seated comfortably with his dominant arm fixed parallel to the floor for 10 minutes. Preliminary experimental results indicated that this exercise intensity corresponded to approximately 20% of maximum voluntary contraction (MVC). Each subject performed the exercise twice, and the surface EMG signal was obtained by unipolar or bipolar configurations during each performance.

The surface EMG signals were recorded by active disc electrodes (material: gold; diameter: 15 mm) with conductive paste, and the electrodes of the bipolar configuration had a center-to-center spacing of 20 mm. The electrodes were located over the biceps brachii of the dominant arm of each subject. The reference electrode and the ground electrode were placed over the olecranon and pisiform, respectively. Each electrode was fixed with medical adhesive tape. Surface EMG signals were amplified and filtered between 2 Hz and 300 Hz and then sampled at 1000 Hz via a dedicated acquisition system (Polymate II AP216, TEAC).

IV. DATA PROCESSING

Two sections (first and last sections) were selected from the digitized surface EMG data of the 10 minutes for fatigue evaluation. The first and last sections were assumed to be 1–2-minute intervals and 8–9-minute intervals of data, respectively. Sixteen epochs were picked from each section for analysis. Each epoch comprised 512 points.

%DET was estimated from each epoch, and the averaged values of corresponding sections of all subjects were obtained. This study investigated whether the %DET of the last section increased relative to that of the first section and also whether the variation of the %DET depends on electrode configuration. MDF was then analyzed in the same manner. Values are presented as means ± SE. The statistical difference was determined by 2-sided Student’s \( t \)-test. A \( P < 0.05 \) was considered statistically significant. Finally, in order to compare the sensitivities of %DET and MDF, the values of %DET and MDF were normalized against the corresponding values of the first sections, which were set to 100%. The variation ratios were compared in all combinations. Multiple comparisons were made by Tukey’s test. All statistical analyses were performed with dedicated software (Ekusru-Toukei 2010, Social Survey Research Information Co., Ltd.).

V. RESULTS AND DISCUSSION

A. Estimation of values of various parameters for RQA

This section describes the procedures for deciding the embedding parameters (time delay \( \tau \) and embedding dimension \( m \)), the threshold distance \( \epsilon \) for the construction of the recurrence plot, and the minimal length \( l_{\text{min}} \) of the diagonal structure for computation of %DET. The embedding parameters and the threshold distance were estimated with respect to each section and each epoch, respectively.

The optimal value of the time delay was estimated using mutual information. The number of bins needed for computation of mutual information was selected using the following equation [7]:

\[
\log_2 N + 1 + \log_2 \left( 1 + \hat{k} \sqrt{N/6} \right)
\]

where \( N \) is the number of data and \( \hat{k} \) is the estimated kurtosis. Figure 1 shows the typical transition of mutual information against the time delay in the surface EMG signals measured by the unipolar configuration in the first section. The time delay \( \tau \) was designated as the time delay of the first local minimum of the mutual information. The values of the time delay estimated for all sections ranged between
3 and 10 ms. The values for the last sections tended to be higher than those for the first sections.

The embedding dimension \( m \) was estimated using the false nearest-neighbors (FNNs) method. The threshold \( R_{tot} \) of the FNNs method was set at 10 [8]. Figure 2 shows the typical relationship between the rates of FNNs and the dimension for the first sections of the surface EMG signals measured by the unipolar configuration. The embedding dimension \( m \) is that at which the rate of FNNs converges to nearly zero. The estimated values of the embedding dimension \( m \) ranged between 3 and 6, and the values for the last sections tended to be larger than those for the first sections.

Based on [9] and the estimated value of \%REC, the threshold distance \( \varepsilon \) was set to 10% of the maximal phase space diameter. The \( L_2 \)-norm (Euclidean norm) was utilized for computations of distance. The values of the threshold distances for the last epochs tended to be greater than those for the first epochs. The minimal length of the diagonal structure \( l_{min} \) was set to 2.

**B. Recurrence plot and estimated \%REC**

Recurrence plot computations were performed using each epoch. Figure 3 shows the typical recurrence plots and associated EMG recordings of the first and last contractions as measured by the unipolar configuration. In this study, the average value of \%REC was nearly 1.8% and did not exceed 10%, as the value of the threshold distance had been adjusted. This strategy is generally recommended in the literature [4].
C. Estimated %DET and MDF

Table 1 gives the average %DET values for all subjects for each combination of section and derivative method. The values of %DET during the last contractions were significantly greater than those during the first contractions regardless of whether the unipolar or bipolar configurations were used ($P < 0.001$). Therefore, muscle fatigue during a low-level isometric contraction could be detected by %DET. In addition, the increase in %DET was 1.5-fold higher ($P < 0.08$) when the unipolar configuration rather than the bipolar configuration were used. Therefore, it remains possible that unipolar configurations are more sensitive than bipolar configurations for the detection of muscle fatigue by %DET.

Table 2 gives the average MDF values for all subjects. The values of MDF during the last contractions were significantly lower than those during the first contractions regardless of whether the unipolar or bipolar configurations were used ($P < 0.001$). Therefore, muscle fatigue could also be detected by MDF in this study. Furthermore, the magnitude of the decrease in MDF was larger ($P < 0.07$) when the unipolar configuration rather than the bipolar configuration were used. Therefore, it remains possible that unipolar configurations are better suited than bipolar configurations for the detection of muscle fatigue by MDF.

D. Normalized variations of %DET and MDF

Table 3 gives the normalized variations of %DET and MDF against the corresponding average values of the first sections. Multiple comparisons testing showed that the normalized variation of %DET measured by the unipolar configuration was significantly larger than that of MDF measured by the bipolar configuration ($P < 0.01$). There was no significant difference for any of the other combinations, although normalized variations of %DET measured by both methods tended to be larger than those of the corresponding MDF measurements. These results suggest that %DET outperforms MDF in terms of fatigue-induced normalized variation.

VI Conclusion

This study attempted to use RQA to detect muscle fatigue during low-level isometric contractions. Our findings suggest that RQA is an effective method for this purpose and that the detection sensitivity of unipolar configurations is greater than that of bipolar configurations. Furthermore, our results suggest that %DET is more sensitive than MDF to fatigue-induced changes. A subsequent study with larger numbers of subjects and epochs should be performed to confirm these properties in greater detail.

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<th>Table 1 Average %DET values for all subjects</th>
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<td>Bipolar configuration</td>
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<td>First section</td>
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<td>(Mean ± SE)</td>
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<th>Table 2 Average MDF values for all subjects</th>
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<tr>
<td>Bipolar configuration</td>
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<tr>
<td>%DET</td>
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<td>0.39 ± 0.08</td>
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<td>(Mean ± SE)</td>
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REFERENCES