A Muscular Fatigue Index using Superimposed M Waves and Fuzzy Rules

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Abstract - A practical muscle fatigue index is proposed in this paper based on the correlation between the instantaneous frequencies (IFs) of the superimposed M wave and the mean power frequency (MPF) of the preceding background activity. We investigate the details of the distribution of a feature vector (*MPF*, *IF*) in the two-dimensional space. The experimental results showed that the correlation coefficients between MPF and IFs was high during a first phase of a sustained contraction and then they became uncorrelated as muscular fatigue progressed. Combining the correlation coefficients and conventional fatigue indices, we propose a fuzzy rule based muscular fatigue index. The fuzzy rule based muscular fatigue index demonstrated an exhausted stage clearer than conventional indices, whereas conventional indices saturated.

I. INTRODUCTION

Assuming that localized muscular fatigue progresses gradually during a sustained contraction, the conventional fatigue indices can be evaluated by comparing them with their initial values [1]. The initial values are sometimes not relied upon, however, when we estimate the degree of muscular fatigue at a certain time during long-term exercise or during dynamic movement. An impulsive response approach based on system identification theory would be useful in developing a new fatigue index because a degree of localized muscle fatigue could be observed by stimulating muscle at a required time. We have proposed a muscular fatigue evaluation method based on the relationship between a superimposed M (SM) wave and the preceding background activity [2]. The SM wave is the electrical elicited M wave superimposed on a voluntary contraction. If the preceding background activity and the SM wave reflect localized muscular fatigue in different ways, the relationship would be effective in developing a muscle fatigue index at an arbitrary time. This paper describes the experimental results of the relationship in the frequency domain and then proposes a practical muscle fatigue index quantified by the fuzzy inference.

II. METHOD

A. Measurements

Nine male subjects (20 - 23 years old) volunteered for this study and were informed of the experimental procedures and risks associated with the muscle fatiguing efforts. Working with the tibialis anterior muscle, we asked subjects to maintain a 70 % maximal voluntary contraction. Each subject was seated in a chair equipped with a force transducer attached to the instep of the foot. We fixed a pair of stimulation pads on the motor point area and obtained the highest SM wave within pain tolerance. The active 4-bar electrode for measuring two-channel ME signals was pasted on the skin parallel to the muscle fibers. One experimental set for each subject consisted of the first 40 s, the middle 100 s, and the last 40 s, separated by resting intervals of 1 min. Total exercise includes three experimental sets with each 5-min resting interval between consecutive sets. The force output and the two single differential ME signals were sampled at 5 kHz with a 14-bit analog-to-digital convertor.

B. Evaluation

The number of epochs in a frame was 5 and thus the number of frames in each M second trial was M - 4. Each epoch including the preceding background activity and the SM wave. The IFs were estimated from each averaged SM wave by using the FFT algorithm. Within each epoch, the MPF of each preceding background activity was estimated before the external trigger signal. Then the averaged MPF was obtained in each frame. After obtaining the time-series of MPF and IFs, the MPF-IF distribution was classified by the discriminant analysis using the Mahalanobis distance into two different classes. We studied the correlation coefficients of two different classes and the time-varying behavior of them in the MPF-IF distribution.

To indicate a more accurate degree of muscular fatigue at a required time, fuzzy inference was employed. As input associants, we used a correlation coefficient in time domain ($\rho_{MPF\text{-}IF}$), a changing ratio of MPF (φ), and a decreasing ratio of ARV (γ). These indices are calculated in each interval from the time-series of ME parameters every 30 sec. The membership functions were designed for reflecting the profile of the MPF-IF distribution in the time domain. The parameters for output associants were designed so that the muscular fatigue index, d_{MF}, could be divided into seven sets equally. For every experimental set, we selected the IF at the specific time that showed the highest correlation coefficient ahead of muscular fatigue evaluation.

III. RESULTS

There were two classes of MPF-IF distributions: the highly correlated class Ω_1 and the almost uncorrelated class Ω_2. Normalized MPF-IF distributions during each middle trial proved that separation of two classes was still meaningful throughout the three experimental sets (**Fig. 1**). The difference between Ω_1 and Ω_2 became apparent when we selected the MPF-IF distribution at the specific time that showed the highest correlation coefficient for Ω_1 in each experimental set. The class Ω_1 usually appeared during the first part of a fatiguing contraction, then Ω_2 arose as muscle fatigue progressed. The results implied that $\rho_{\text{MPF-IF}}$ decreased as muscle fatigue progressed. This feature was meaningfully demonstrated through the first to middle trials for IFs at the first peak or the zero crossing.

Figure 2 shows the basic statistics of the degree of muscular fatigue index, d_{MF}, and the parameters for membership functions at every interval within subjects. The mean of d_{MF} indicated heavy condition at the latter part of the middle and last trials. It is important that $\rho_{\text{MPF-IF}}$ changed from high to low as muscle fatigue progressed. The slight decrease in φ_k and the increase in γ_k appeared as muscular fatigue progressed, but they finally saturated where the exhausted phase was expected. The behavior of d_{MF} agreed with the self-reports.

IV. DISCUSSION

The features of fast twitch motor units probably produced the highly correlated class Ω_1, because they appeared to contribute steep reductions in the MPF and IFs during the beginning phase of a fatiguing contraction. Both the degenerated muscle activity and the peripheral effect by the supramaximal stimulation on the motor point may have produced the uncorrelated class Ω_2. The supramaximal stimulation seemed to sustain the original shape of the SM wave, even if motor unit action potentials were continuously degenerated in the preceding background activity during the latter phase of muscular fatigue.

The practical application demands estimating multivariate ME parameters and appropriate decision rules to accept the individual differences. Moreover, the limitations of the field experiments (for example, the application for patients under rehabilitation) bring about some errors for estimating multivariate ME parameters. Introducing fuzzy inference was an effective approach to develop a muscular fatigue index from the combination of the time-varying features of the MPF-IF distribution and conventional muscle fatigue indices. Further studies will be required for customizing the membership functions and fuzzy rules in each practical field.

V. CONCLUSION

Two different distributions provided by the relationship between IFs at specific local times of the superimposed M wave and the MPF of the preceding background activity were observed as muscular fatigue progressed. A highly correlated MPF-IF distribution appeared during the beginning phase of a fatiguing contraction and an uncorrelated MPF-IF distribution was observed during the latter phase of muscular fatigue. Such a difference was noticeable when the IF around the first part of the superimposed M wave was selected in each experimental set in addition to using the correlation coefficients. Combining the correlation coefficients and conventional fatigue indices, we proposed a fuzzy rule based muscular fatigue index. The fuzzy rule based muscular fatigue index indicated an exhausted stage more distinctly than conventional indices.

Acknowledgements

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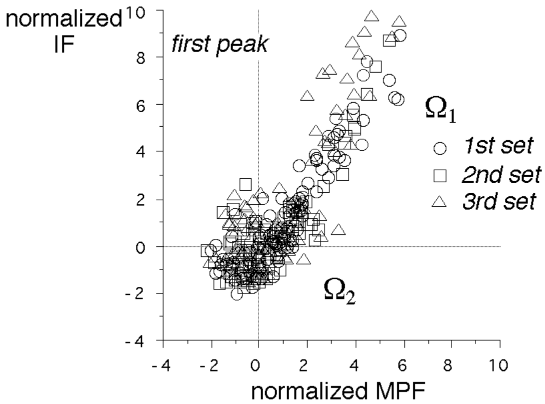

Fig. 1. Normalized MPF-IF distribution.

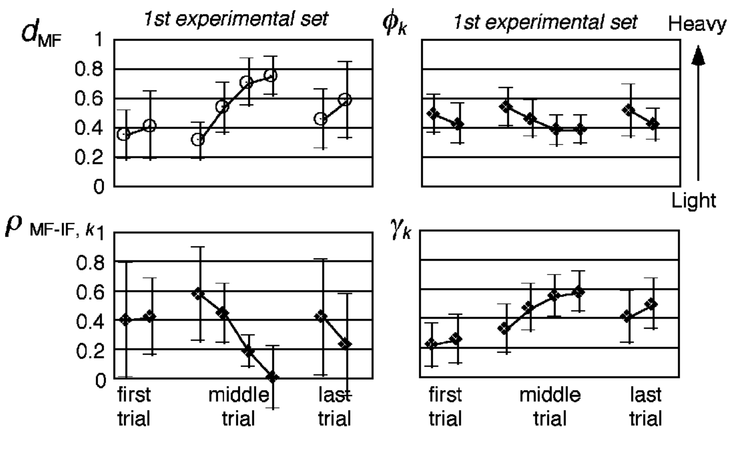

Fig. 2. Fuzzy rule based muscle fatigue index.