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Abstract

In this work a torque assessment approach is presented to estimate FES-induced torque no matter the muscle is fatigued or not in interrupted stimulation. This approach is based on evoked EMG (eEMG) signal and use peak-to-peak (PTP) amplitude and second phase area (SPA) to correlate eEMG and torque. The mapping function is built with pooled data of recruitment test and fatigue test in two complete paraplegic subjects. In this model, PTP is mainly responsible to the effect of recruitment level, SPA is mainly responsible to the muscle fatigue phenomenon. The model is fitted to the measured recruitment curves and measured fatigue curves and shows good fits, with R^2 values above 0.95 and 0.93 for each subject. This suggests that it is possible to use processed eEMG signal to change stimulation intensity to obtain desired trajectory even when stimulated muscle is fatigued or to inform the fatigue condition.

Keywords-Torque assessment, evoked EMG, fatigue.

1 Introduction

FES has been used to restore motor function or produce movements in SCI patients. The main applications include the support of walking, standing, grasping objects and drop foot correction. Nevertheless, the muscle fatigue phenomenon and the inadequacy of force sensor limit the accuracy of FES control. Muscle fatigue leads the inability to maintain or reach the target level of induced force in continuous and interrupted stimulation. In SCI patients, due to the lack of sensory feedback from the muscles to indicate fatigue state, it is essential to monitor muscle state and assess the generated force to compensate the fatigue and achieve the desired trajectory. It is also important to cease the stimulation depending on muscle fatigue to prevent serious muscle damage. However, the implanted force sensors are nearly unavailable. It is required to use other measurements as alternative of muscle force sensor to estimate muscle force generated by electrical stimulation.

As evoked EMG (eEMG) by FES can capture all neural excitation of stimulated muscle, including the stimulation signal directly from stimulation, as well as from other sources, such as reflex, spasticity and fatigue, it has been used as fatigue index or force sensor in previous researches[1]-[6]. The eEMG signal consists of repetitive m-wave due to synchronous activity of all motor units. In the course of stimulation, the change of muscle force is accompanied by a change in EMG signal. Previous works using eEMG to indicate fatigue or predict muscle force have been done mainly for continuous stimulation [1]-[3]. In this case, sustained force can be obtained due to sustained stimulus impulse applied to muscle. The muscle activity represents as post-tetanic potentiation, primary fatigue and maximal fatigue [4]. The force and PTP (peak-to-peak) amplitude decrease rapidly and level off at low force and PTP values after less than 2 minutes in continuous stimulation [4]. Some amplitude and frequency related m-wave parameters were used to correlate the eEMG-force relationship. MAV (mean-absolute-value) was used to model eEMG-torque relationship [1]. In [2], RMS (root-mean-square) and median frequency manifested to follow the changes of isometric torque well. In [3], SPA (second phase area) and RMS were proposed to build fatigue index for assessing muscle fatigue. However, this paper did not attempt to predict force with eEMG. In interrupted stimulation, the stimulation and some rests are set in sequence, which can reduce muscle fatigue. It is a more realistic way of stimulation as the muscle is not stimulated all the time. But muscle recovery should be considered along with muscle fatigue, which complicates the eEMG-force relationship. As it was indicated in [4], both PTP and force behave quite differently during recovery. They showed that after 5 min of continuous stimulation, both force and PTP values drop to similarly low levels and then PTP recovers to its initial value after only 1 min, whereas force never recovers above 40% of its initial value. Thus, few works focus on the eEMG-force model in interrupted stimulation. The relationship between force and PTP was described by exponential function in interrupted stimulation [5]. In [6], PTP is characterized as positive correlation with muscle force during cycling movement. It was suggested to use interrupted stimulation to reduce fatigue. In this work, we present a study carried out to evaluate the changes of the m-wave and assess FES induced muscle torque in the complete paraplegic patients in interrupted stimulation, no matter the muscle is fatigued or not.

2 Methods

Experiments were performed on two complete paraplegic subjects in ASIA A. The tibialis anterior muscle was stimulated via transcutaneous stimulation. Subjects were seated in the chair with the right foot fixed on a Biodex dynamometer. Stimulus-evoked EMG signal was detected using surface electrodes in a bipolar electrode arrangement. The EMG electrodes were placed halfway between two stimulation electrodes and oriented parallel to the muscle fibre. The reference electrode was placed on the patella of the knee. The surface stimulation electrodes were placed approximately over the muscle belly. Signal acquisition of ankle torque and eEMG was sampled at 4096Hz simultaneously.

Each subject participated in two sessions, recruitment protocol and fatigue protocol. These two sessions were performed in sequence with the same positioning and set-up as described above. The stimulation pattern was a periodic ramp-hold-ramp signal. Recruitment test was done firstly with amplitude modulation at constant frequency (20Hz) and constant pulse width (450μs). The amplitude was increased in every 2.5mA. A resting period of 10-s was enforced between each trial. In the following fatigue test, the stimulation was delivered with constant frequency (20Hz), constant pulse width and certain maximal amplitude (subject2: 52.5mA; subject3: 37.5mA). 3 series of 5 trains stimulation which consists of 3-s stimulation and 2.2-s rest were performed for interrupted fatigue protocol.

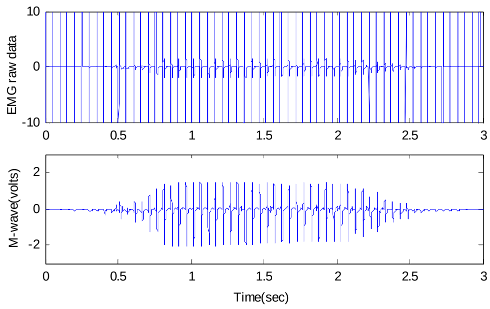

Figure 1 An example of eEMG raw signal and m-wave extracted by blanking window.

Under electrically stimulation the motor units have synchronous activity which is represented as m-wave. However, with surface stimulation m-wave is contaminated by stimulation artifact which is generated due to the electronic field interaction. In order to analyze the evoked EMG of electrically activated muscle, the first step is suppression of the stimulus artifact. Different approaches have been proposed by some researchers [1][2]. We found the main phase of artifact was included in the first 3ms from the onset of stimulation, and there was a time delay of about 7ms from the stimulation onset to the first spike of m-wave. Through blanking window method, the stimulation artifact was removed and the m-wave was extracted, as shown in Figure 1.

For the analysis of the changes of m-wave, the eEMG signal was subdivided in epochs, so that each one of them corresponded to one m-wave by stimulation pulse. The m-wave parameters, such as RMS, PTP, and SPA were calculated from m-wave, as shown in Figure 2.

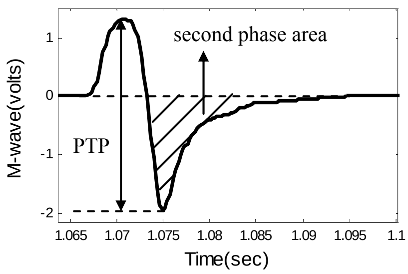

Figure 2 An example of a single m-wave response taken from subject2 after stimulation artifact suppression.

3 Results

For both recruitment test and fatigue test, the average of the torque's plateau generated by each stimulation train was calculated along with the average of m-wave parameters in the same period.

In the above figure of Figure 3, average PTP and average torque corresponding to each stimulation level in recruitment tests are plotted for both subjects. In the bottom, average SPA and average torque corresponding to each fatigue level in fatigue tests are plotted for both subjects. The results show that PTP positively correlates to the torque with increasing stimulation level in recruitment test. SPA was found to be inversely correlated to the torque with increasing total stimulation duration in fatigue test. Correlation coefficient r is shown in each plot.

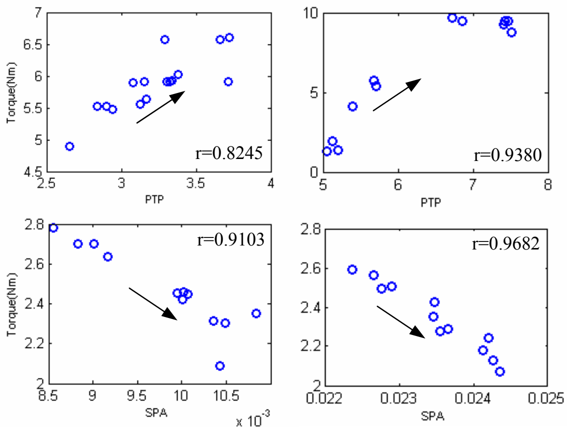

Figure 3 The correlation between PTP and torque in recruitment test for two subjects (top).The arrows indicate stimulation amplitude increasing. The correlation between SPA and torque in fatigue test for two subjects (bottom). The arrows indicate total stimulation duration increasing.

According to the above correlations, linear regression was executed to model the relationship between torque and m-wave parameters.

We define the FES induced torque related to PTP and SPA by

$y=\beta_1 x_1+\beta_2 x_2+\varepsilon$

Where y is generated torque, x_1 is PTP of eEMG and x_2 is SPA of eEMG. The ε is an error term.

By means of ordinary linear square regression, the mapping function is built with the given data sets of recruitment test and fatigue test to minimize the sum of squared residuals.

At first, the generated mapping function for each subject was validated using the original data sets. The coefficients of determination (R^2) between estimated and measured torque are respectively 0.9525 for subject 2 and 0.9334 for subject 3.

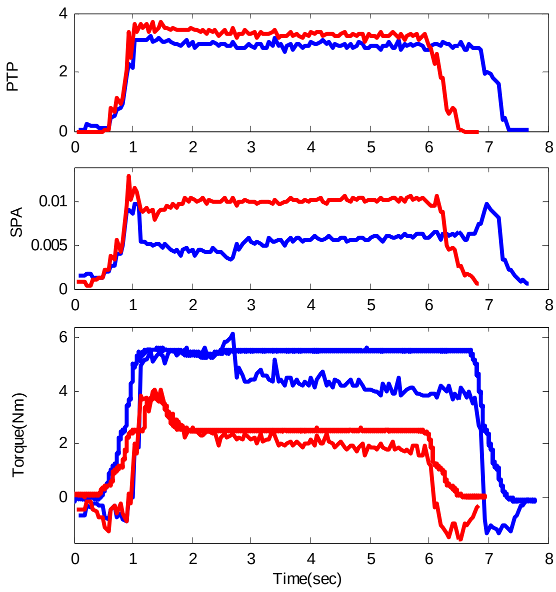

Figure 4 Non-fatigued (blue) and fatigued (red) PTP, SPA and torque in the same stimulation amplitude. The measured (smooth line) and estimated (non-smooth line) torque obtained using the above eEMG-torque model (bottom).

Next, the mapping function was applied for the data sets which were not used for linear regression. In Figure 4, the same stimulation amplitude is applied, and blue line indicates the stimulation at the beginning of whole tests in non-fatigue condition, the red line indicates the stimulation after recruitment test. Torque was decreased to about 45% due to muscle fatigue, while PTP was not decreased due to the recovery in the interrupted stimulation. The estimated torque can nearly track the torque changes. At the beginning and end of stimulation, low stimulation intensity in the ramp generates weak muscle response, the eEMG signal does not represent as typical biphasic m-wave. It is difficult to get accurate PTP and SPA value. Consequently, the fixed parameter model underestimated the output torque. In this initial trial, we aim at estimating the plateau of torque. The RMS error between estimated and measured torque in the plateau were 1.1440 for non-fatigued and 0.4848 for fatigued muscle.

4 Discussion and Conclusions

In previous works, PTP is usually used to correlate the relationship between EMG and force. It also shows good performance in recruitment test in our work. However, in interrupted fatigue test, due to the different recovery speed for the torque and the amplitude of EMG signal, the PTP does not represent any difference after some rests, as this phenomenon was previously reported [4]. SPA of eEMG could compensate to reproduce the difference of torque. A possible explanation for this phenomenon is that during the rest duration of interrupted stimulation, peak amplitude of eEMG recovers faster than torque, the PTP does not demonstrate difference. However, due to the reduction of action potential conduction velocity by fatigue, the second phase duration increases, as a result, we can find the difference in the SPA with the decay of torque. It can be suggested that eEMG can be used to predict torque even if muscle is fatigued even in interrupted stimulation and would contribute to precise control of torque in FES. The further investigation is required for the better interpretation of eEMG.

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Acknowledgements

This work was partly supported by a scholarship from China Scholarship Council.