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Tools and techniques

A simulation study on the relation between the motor unit depth and action potential from multi-channel surface electromyography recordings

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A R T I C L E I N F O

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A B S T R A C T

To investigate the spatial information of individual motor unit (MUs) using multi-channel surface electromyography (EMG) decomposition. The K-means clustering convolution kernel compensation (KmCKC) approach was employed to detect the innervation pulse trains (IPTs) from the simulated surface EMG signals, and the motor unit action potentials (MUAPs) were evaluated using the spike-triggered average (STA) technique. The relationships between the features of MUAP and MU depth were determinated with a least square fitting method. The errors of peak-to-peak (PTP) amplitude of reconstructed MUAPs were less than 5.73%, even with 0 dB signal-to-noise (SNR). The fitting errors with nonlinear model were less than 5.55% for SNRs higher than 20 dB. The results show that it is possible to provide a useful method for estimating MU depth from surface EMG recordings. It is expected to extend the applicability of surface EMG technique to more challenging clinical applications.

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1. Introduction

Surface electromyography (EMG) and intramuscular electromyography (IEMG) are two kinds of technique in widespread use for muscle activity recording [1]. IEMG contributes significantly to the diagnosis of neuromuscular disorders. However, its invasiveness is a serious obstacle to limit its applications in clinic, especially in the long-term investigation to monitor the natural progression of disease. Moreover, the subject risks of traumatic or infection cannot be overlooked, and that it is painful is a well-recognized trap. Surface EMG could remove these drawbacks [2]. Surface EMG is a non-invasive technique to record muscle activities by placing electrodes on the skin above a muscle, but its poor spatial resolution limits its role. Therefore, to be a satisfactory substitute for IEMG, the spatial information and specificity would need to be investigated.

The surface EMG signal is essentially comprised of the sum of motor unit action potentials (MUAPs) from different MUs with the recording range of the electrode. The amplitude of surface EMG is dependent on motor unit (MU) size, the number of MUs, and MU depth. In general, the waveform of a MUAP is determinated by the relative position of the surface recording electrode and the muscle fiber distribution within the MU. In kinesiology and rehabilitation medicine, MU depth is desired on which muscles are active [3], then the target muscles can be determined and studied. In addition, stroke represents a huge health problem with the subsequent incident of spasticity in post-stoke survivors. Botulinum neurotoxin (BTX) injection has proven to be a relatively safe treatment for focal spasticity management, and it is important to accurately identify the locations of MU of spastic muscles, so as to guide BTX injections. It has been demonstrated that increasing injection distance by 1 cm indicated by the innervation zone of MUs, reduced the adverse effects of BTX by 46% [4]. So, it is very important to identify the depth of MUs for the best clinical outcome with a minimal. However, there is little work of using surface EMG to study MU depth and its details.

The problem in investigating the location of individual MUs is two aspects. Firstly, the extraction of MUAPs form surface EMG recordings, and secondly the relation between MU location and the MUAP amplitude [5]. A number of methods [6–9] have been developed over last decade to decompose surface EMG recordings into innervation pulse trains (IPTs), which can be further employed to extract MUAPs. Furthermore, it can be quantified how the MUAP amplitude depends on MU depth. When the radial distance between the surface electrode and MU increases in the direction perpendicular to the muscle fiber direction, a rapid decrease in MUAP amplitude can be observed [10–12]. However, the results presented by these authors use different muscles or recording

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electrodes of different types, which may affect the relationship. Therefore, the relations between between MUAP parameters and MU depth remains unmet.

Many neuromuscular disorders cause changes in the MUAP shape. In clinical neurophysiology, the size of MU may change as a result of some neuromuscular diseases [5]. The size of MU can be estimated by normalized MUAPs. The change in MUAP amplitude on skin surface perpendicular to muscle fiber direction contains spatial information of the MU. The methods to estimate MU location from surface EMG recordings have been proposed [3,11,12]. However, because of lack of the actual depth information of the MUs, these studies haven't been validated systematically.

In this study, the relation [11,13] between MUAP parameters and location of the MU were tested with simulated surface EMG. We present a method that combines earlier algorithm in surface EMG decomposition [8] and experience offered by spike triggered average (STA) [14] to study the depth information of MUs. So far the decomposition algorithm have been hardly applied to the location information of individual MUs.

2. Methods

The surface EMG model is considered as the summation of contributions from the muscle fibers. Each MU consists of a motor neuron and the muscle fibers scattered within a cylindrical volume. First of all, the surface EMG generation model and detection system is introduced in this study. Each generated signal was corrupted by Gaussian noises with the signal-to-noises (SNRs) being set to 0 dB, 10 dB, 20 dB, 25 dB, and 30 dB, respectively. Next, the KmCKC approach is employed for surface EMG decomposition, and the MUAP of each MU is extracted. Finally, the relations between MUAP parameters and MU depth are investigated. The flowchart of the surface EMG signal processing in this study is shown in Fig. 1.

2.1. Surface EMG model

Many surface EMG generation models have been proposed and applied for investigation of the relation between a current density source in the muscle and the potential distribution over the skin. The surface EMG modeling process consists of providing a mathematical description of the action potential and deteminating the surface potential.

The mathematical description of the action potential has been reported by Rossenfalk [15] and Merletti [16]. The current distribution shows a triphasic shape, so we consider the contribution of each muscle fiber to surface potential over the shin as two tripoles propagating in opposite directions with the same velocity from neuromuscular junction to tendon endings. The fiber action potential would be represented by three independent poles. The tripole equations are reported in (1) and (2):

$$P_1 + P_2 + P_2 = 0 \tag{1}$$

$$aP_2 + bP_3 = 0 \tag{2}$$

The model between the surface potential detected by a point electrode and the source is expressed as shown in (3), where electric conductivity is $\sigma_x = \sigma_y = \sigma_r \neq \sigma_z$, and $K_\alpha = \sigma_z/\sigma_r$, $P_i(x_i, y_i, z_i)$ is the $\boldsymbol{i\_th}$ pole. We assume the tissue is modeled as a homogeneous and anisotropic conductor with no frequency dependence. The action potential of each individual fiber is added to give the contribution of MUAP to the surface potential distribution. The model has been acceptable by other investigators [16–19] and is used in this work.

$$\varphi_j = \frac{1}{2\pi\sigma_r}\sum_{i=1}^{6}\frac{P_i(x_i, y_i, z_i)}{\sqrt{K_\alpha\left((x - x_i)^2 + (y - y_i)^2\right) + (z - z_i)^2}} \tag{3}$$

The surface EMG signals were recorded with 77-channel surface electrode array, as shown in Fig. 2, which was parallel to the muscle fiber.

2.2. KmCKC approach

The K-means clustering and convolution kernel compensation (KmCKC) approach [4,8] was utilized to decompose the simulated surface EMG signals into constituent MUAP trains. The spike-triggered average (STA) technique can be expected to accurately and efficiently identify the single MUAP. The KmCKC approach has been validated extensively with both experimental and simulated signals [8]. The K-means clustering is performed as an initial step to cluster firing times of the same MU. The MUAP trains can be estimated during this process by choosing an appropriate number of clustered groups so that most of discharge instants fired by the same MU can be gathered into one group. Then an iterative convolution kernel compensation (CKC) method is employed to update the estimated MUAP trains.

In the bipolar MUAP maps, the opposite phases appear because of the surface EMG signals traveling in opposite directions. Therefore, the position of the innervation zone (IZ) can be localized from

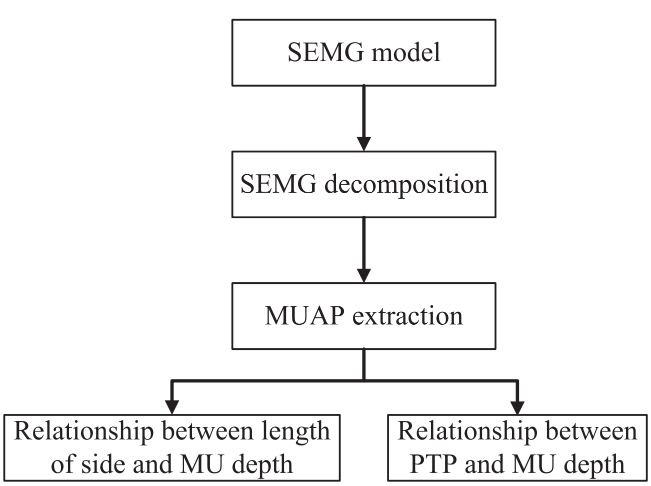

Fig. 1. Flowchart of surface EMG signal processing.

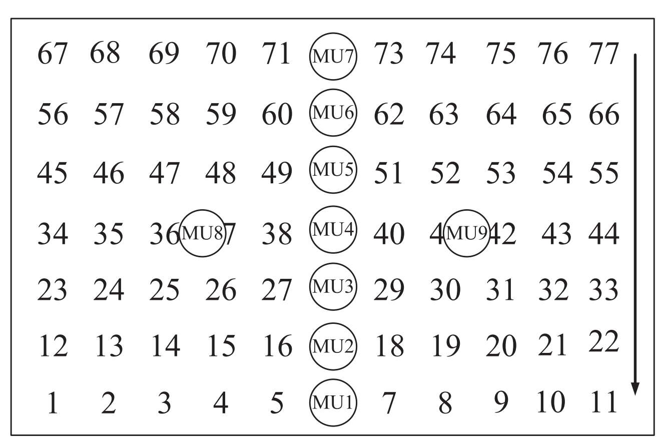

Fig. 2. The distribution of 77-channel surface EMG recording electrodes (7*11 arrays with the center to center electrode distance of 9 mm) and the position of MU1-MU9 on the surface. The arrow represents the muscle fiber direction.

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