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Motor unit number estimation based on high-density surface electromyography decomposition

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HIGHLIGHTS

- The novel MUNE method employs high density surface EMG decomposition to characterize SMUP signals.
- A large number (>20) of SMUPs can be obtained at each contraction with a good match with the CMAP.
- The new MUNE works for proximal muscles without intramuscular electrodes or multiple stimuli.

ABSTRACT

Objective: To advance the motor unit number estimation (MUNE) technique using high density surface electromyography (EMG) decomposition.
Methods: The K-means clustering convolution kernel compensation algorithm was employed to detect the single motor unit potentials (SMUPs) from high-density surface EMG recordings of the biceps brachii muscles in eight healthy subjects. Contraction forces were controlled at 10%, 20% and 30% of the maximal voluntary contraction (MVC). Achieved MUNE results and the representativeness of the SMUP pools were evaluated using a high-density weighted-average method.
Results: Mean numbers of motor units were estimated as 288 ± 132, 155 ± 87, 107 ± 99 and 132 ± 61 by using the developed new MUNE at 10%, 20%, 30% and 10–30% MVCs, respectively. Over 20 SMUPs were obtained at each contraction level, and the mean residual variances were lower than 10%.
Conclusions: The new MUNE method allows a convenient and non-invasive collection of a large size of SMUP pool with great representativeness. It provides a useful tool for estimating the motor unit number of proximal muscles.
Significance: The present new MUNE method successfully avoids the use of intramuscular electrodes or multiple electrical stimuli which is required in currently available MUNE techniques; as such the new MUNE method can minimize patient discomfort for MUNE tests.

1. Introduction

Motor unit number estimation (MUNE) techniques are clinically useful by estimating the number of functioning motor units in a muscle, which can serve as a biomarker for the progression of motor neuron diseases or neuromuscular disorders. Various MUNE methods have been developed since the incremental counting technique was introduced in 1971 (McComas et al., 1971). The main limitation with the incremental counting technique is the

Abbreviations: MUNE, motor unit number estimation; MPS, multiple-point stimulation; STA, spike-triggered average; DE-STA, decomposition enhanced spike-triggered average; EMG, electromyography; HD, high-density; SMUP, single motor unit potential; CMAP, compound muscle action potential; MVC, maximal voluntary contraction; CKC, convolution kernel compensation; KmCKC, K-means clustering convolution kernel compensation.

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problem known as "alternation", which leads to an erroneous overestimation of the MUNE. This problem attributes to the procedure that all stimuli are applied at a single site of the nerve, which results in possible alternative activations of two or more motor neurons at an incremental stimulus and complicates the separation of single motor neurons.

The multiple-point stimulation (MPS) method was then developed to solve this problem by activating different single axons at different sites along nerves (Kadrie et al., 1976; Doherty and Brown, 1993). However, the MPS MUNE is not applicable to proximal muscles, as it is difficult to stimulate a proximal nerve at enough sites to obtain a sufficient amount of single motor unit potentials (SMUPs) (Gooch et al., 2014). This limitation also challenges the statistical method (Gooch et al., 2014), possibly because of the difficulty in steadily sustaining a large number of stimuli at several levels of intensity at proximal nerves that are often with a poor accessibility. Alternatively, the spike-triggered average (STA) method and its variation, the decomposition enhanced spike-triggered average (DE-STA) method, were developed to overcome this limitation (Doherty and Stashuk, 2003; Boe et al., 2004, 2005). The STA and DE-STA methods can be performed on both distal and proximal muscles, as SMUPs are obtained from voluntary contractions rather than multiple-points stimulation along nerve courses. However, the need of using intramuscular needle electromyography (EMG) electrodes to obtain the triggers for the construction of the SMUP pool in the STA or DE-STA methods makes them an invasive approach and demands much patient tolerance. A more advanced MUNE technique that is non-invasive and not limited to distal muscles will greatly help extend the applicability of current MUNE methods.

High density (HD) surface EMG techniques have become a powerful tool for clinical neurophysiology (Merletti et al., 2009; Van Dijk Johannes, 2012; Li et al., 2015; Yao et al., 2015). Non-invasive HD surface EMG recordings can be decomposed into constituent motor unit action potential trains which can be further employed to extract SMUPs in a non-invasive manner for MUNE studies. Many surface EMG decomposition algorithms have been developed over the last decade (Holobar and Zazula, 2007a,b; Kleine et al., 2007; Ning et al., 2015; Chen and Zhou, 2016) and undergone extensive investigations and validations (Holobar et al., 2010; Marateb et al., 2011; Almousa et al., 2015; Liu et al., 2015) in human. However, these algorithms have yet been applied to MUNE for the extraction of SMUP samples. Van Dijk and coworkers recently pioneered the application of the HD surface EMG in MUNE (van Dijk et al., 2008, 2010a,b). This method offered a comprehensive way to calculate MUNE and evaluate the representativeness of SMUP samples based on the HD information. However, this HD MUNE was essentially based on the multiple-points stimulation and therefore the applicability to proximal muscles remains unmet.

In this study, we present a new MUNE method that combines our earlier experience in HD surface EMG decomposition (Liu et al., 2015; Ning et al., 2015) and advantages offered by existing HD MUNE methods (van Dijk et al., 2008). This new method is non-invasive in nature and not limited by the locations of muscle.

2. Methods

2.1. Subjects

A total of 8 healthy and physically active male subjects (mean age: 29 ± 4) participated in this study, and none of them has a history of peripheral nerve disease. The research protocol was approved by the local ethic committee and all subjects were fully informed of the purpose and goal of the study and gave informed consents. The biceps brachii muscles of the dominant hand were investigated.

2.2. Stimulating and recording systems

The musculocutaneous nerve was stimulated using the DS7 current stimulator (Digitimer Ltd, Welwyn Garden City, United Kingdom) with a bipolar stimulating electrode by an experienced physician (S.L.). High-density surface EMG signals of the biceps brachii muscles were recorded using two 2 flexible 8×8 arrays (TMSi, Enschede, The Netherlands) with an electrode diameter of 4.5 mm, and a center-to-center electrode distance of 8.5 mm, as shown in Fig. 1a. This HD EMG grid showed great competency in our previous EMG analysis including EMG decomposition (Liu et al., 2015). The EMG signals were acquired by a 136 channel Refa amplifier (TMSi, Enschede, The Netherlands) at a sampling rate of 2048 Hz per channel and stored in a personal laptop for offline analysis.

2.3. Experimental protocol

An earlier study demonstrated that the force level is an important factor to consider when utilizing voluntary contractions to provide SMUPs (Boe et al., 2005). Therefore, contraction force levels were rigorously controlled in our study. Each subject was seated upright in a mobile Biodex chair (Biodex, Shirley, NY) with a standard 6 degrees-of-freedom load cell (ATI Inc, Apex, NC) setup used to accurately record the isometric contraction force of the biceps brachii during flexion. The forearm and wrist were mounted on a plastic platform inside a fiberglass cast (Fig. 1b). A ring-mount interface was used to strap the wrist in a partial pronation position. This standard position served to minimize spurious force contributions from unrecorded muscles. The skin above the biceps brachii muscle was slightly abraded and cleaned. Two EMG grids were placed adjacently over the muscle belly and longitudinally along the muscle fiber direction. Double-sided tapes with electrode-matched holes were used to stick the grid surface to the skin to enhance the electrode-tissue contact with the help of conductive gels. The reference electrode was placed on the skin above the elbow of the arm on the same side of the EMG grids. A strap ground electrode was wrapped around the wrist on the contrary side. Monopolar surface EMG signals were obtained at each channel relative to the reference electrode.

The protocol to obtain the compound muscle action potential (CMAP) was adopted from our previous study (Li et al., 2014). Briefly, trial electrical stimulation was first performed in an attempt to determine the optimal stimulation position that produced the maximal evoked CMAP. After the optimal stimulation position was localized and fixed, a series of stimuli was delivered with the stimulus strength increasing manually from 5 mA (in increments of 5 mA) to the strength when a supramaximal response was reached. Each stimulus was a rectangular pulse with a width of 200 μs. The supramaximal stimulation was repeated for three times and the largest one was chosen as the source for the CMAP signal. After the stimulation, participants were asked to perform maximal voluntary contractions (MVCs) for three times with the contraction force vector in the x and z direction measured, as shown in Fig. 1. The averaged force vector was taken as the effective MVC. Subsequently, the participants were asked to perform a series of voluntary contractions at different percentage levels of MVC with visual feedback displayed on the computer screen controlled by a load cell (Fig. 1d). For each subject, voluntary contractions were performed at three levels (10%, 20% and 30% MVC) and repeated for 3 times at each level. Each repetition lasted approximately 8 s. Subjects were given sufficient recovery time between any two consecutive contractions to minimize fatigue. The order