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Averaging methods for extracting representative waveforms from motor unit action potential trains

Armando Malanda [a,*], Javier Navallas [a], Javier Rodriguez-Falces [a], Ignacio Rodriguez-Carreño [b], Luis Gila [c]

[a] Electrical and Electronics Department, Public University of Navarre, Spain
[b] Economics Dept., University of Navarre, Spain
[c] Neurophysiology Service, Navarre Hospital Complex, Spain

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ABSTRACT

In the context of quantitative electromyography (EMG), it is of major interest to obtain a waveform that faithfully represents the set of potentials that constitute a motor unit action potential (MUAP) train. From this waveform, various parameters can be determined in order to characterize the MUAP for diagnostic analysis.

The aim of this work was to conduct a thorough, in-depth review, evaluation and comparison of state-of-the-art methods for composing waveforms representative of MUAP trains. We evaluated nine averaging methods: Ensemble (EA), Median (MA), Weighted (WA), Five-closest (FCA), MultiMUP (MMA), Split-sweep median (SSMA), Sorted (SA), Trimmed (TA) and Robust (RA) in terms of three general-purpose signal processing figures of merit (SPMF) and seven clinically-used MUAP waveform parameters (MWP). The convergence rate of the methods was assessed as the number of potentials per MUAP train (NPM) required to reach a level of performance that was not significantly improved by increasing this number. Test material comprised 78 MUAP trains obtained from the *tibialis anterioris* of seven healthy subjects.

Error measurements related to all SPMF and MWP parameters except MUAP amplitude descended asymptotically with increasing NPM for all methods. MUAP amplitude showed a consistent bias (around 4% for EA and SA and 1–2% for the rest). MA, TA and SSMA had the lowest SPMF and MWP error figures. Therefore, these methods most accurately preserve and represent MUAP physiological information of utility in clinical medical practice. The other methods, particularly WA, performed noticeably worse. Convergence rate was similar for all methods, with NPM values averaged among the nine methods, which ranged from 10 to 40, depending on the waveform parameter evaluated.

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1. Introduction

Motor unit action potential (MUAP) analysis is an essential aspect of clinical electromyography (EMG). MUAP trains of active motor units can be recorded by means of intramuscular electrodes. Several potentials from these trains can be isolated, forming what we will refer to as *MUAP trains*. From each of these sets, a waveform representative of the MUAP can be extracted and quantified by means of different waveform parameters (duration, area, amplitude, irregularity, etc.) (Stålberg et al., 1986; Zalewska and Hausmanowa-Petrusewicz, 1995; Nandedkar, 2002; Kimura, 2002) that provide information about the motor units size, structure and function. The reliability of the results deriving from such analysis is largely dependent on how well this waveform represents the underlying bioelectrical phenomena. In particular, the morphological features present in this waveform should have a physiological origin in the motor units, rather than be caused by noise or artefacts from the recording system or the way in which EMG signals have been processed.

Manual, semiautomatic and automatic methods may be used for extracting MUAP trains from EMG signals, each approach having certain problems or limitations. The basic manual method is

Abbreviations: DEP, derivative error power; EA, ensemble averaging; EMG, electromyography; FCA, five-closest averaging; GSMW, gold standard MUAP waveforms; MA, median averaging; MMA, MultiMUP averaging; MUAP, motor unit action potential; MWP, MUAP waveform parameters; NEP, normalized error power; NPM, number of potentials per MUAP; RA, robust averaging; REP, residual error power; SA, sorted averaging; SLER, significantly large errors range; SPMF, signal processing merit figures; SSA, split-sweep averaging; SSMA, Split-sweep median averaging; TA, trimmed averaging; TMA, template matching approach; WA, weighted averaging.

* Corresponding author at: Electrical and Electronics Department, Public University of Navarre, Campus de Arrosadía, 31006 Pamplona, Spain. Tel.: +34 948 169312; fax: +34 948 169720.

E-mail address: malanda@unavarra.es (A. Malanda).

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the extraction of individual potentials. However, lacking waveforms for comparison, a single potential provides few clues as to be sure about what is physiological and what is not, as it may contain spurious morphological features due to noise or waveform contamination of diverse origin. A more sophisticated manual method uses a trigger and a delay line (Nandedkar, 2002). All potentials with amplitude over a manually set threshold are captured and averaged. The subject must only effect slight muscle contractions, and care must be taken by the electromyographer to select only potentials from a single motor unit. In practice, however, MUAPs from different motor units frequently find their way into the MUAP train, and the resulting averaged waveform is therefore contaminated.

A semiautomatic approach implemented in commercial EMG recording systems is the selection and subsequent averaging of the closest potentials according to a certain similarity criterion. Similarity is usually measured in the principal spike of the potential, which may hide important differences in the waveforms outside this spike. If, however, the analysis window goes beyond the principal spike, distortions in marginal parts of the potential may have an excessive influence on the selection and averaging processes.

MultiMUP analysis (Stålberg et al., 1995; Nandedkar et al., 1995) and *EMG decomposition* (Merletti and Parker, 2004) are two approaches to automatic extraction. Both try to separate trains of potentials from different motor units that are firing simultaneously. The purpose of MultiMUP analysis is to obtain the waveforms of the different MUAP trains, isolating a number of seemingly "clean" potentials. The aim of EMG decomposition, on the other hand, is to detect every single potential in the EMG signal and identify it as belonging to one of the MUAP trains present, so that detailed temporal information about the firings of these trains can be made available.

Under both approaches, the set of MUAPs obtained usually represent actual MUAP trains only in an incomplete and noisy manner, because of several factors: erroneous inclusion of potentials from other MUAP trains, distortion of MUAP potentials by potentials from other motor units, baseline wander caused by electrode movement and noise from electronic equipment. The greater the level of muscle activation, the greater the number of MUAP trains present in the EMG signal, and therefore the higher the probability of MUAP superposition and misclassification, which degrade the performance of these techniques. In order to build representative MUAP waveforms that minimize the effects of the above-mentioned noise and interference factors, several techniques have been developed. Prior to their application, the potentials in the train are time-aligned. Alignment is usually carried out by superposing the different potentials in the train so that their maximum negative peaks or their triggering points coincide in time. Alternatively, they may be aligned on the basis of maximum correlation (Campos et al., 2000).

The aim of this paper is to review, test and compare the published techniques available for extracting MUAP-representative waveforms from MUAP trains. In the next section we describe published techniques, including averaging techniques that have been used to build representative waveforms in other contexts, such as event-related potentials or electrocardiographic pulses. Several features conceived to characterize these techniques are presented. We implemented the most relevant of the techniques and tested them with real MUAP trains extracted from EMG signals taken from the *tibialis anterioris* muscle of healthy subjects. In Section 3 we describe the material and subjects used in the study. In Section 4, we provide essential implementation details of those methods included in the study and describe the figures of merit and the gold standard used in comparisons. Results of the comparative evaluation are provided in Section 5 and discussed (Section 6) before we draw up our conclusions (Section7).

2. State of the art

In the following paragraphs we briefly describe published techniques for extracting waveforms representative of MUAP trains.

Ensemble (simple) *averaging (EA)* (Sörmo and Lagunas, 2005) is the most common approach applied for extracting representative waveforms from trains of repetitive potentials and has been used with different sorts of signals: evoked potentials in EEG (Vedel-Larsen et al., 2010), cardiac cycles in electrocardiography (Alperin and Sadeh, 1986) or MUAPs in EMG (Brownell et al., 2006). The EA technique is simple and intuitive and gives satisfactory results at low and uniform levels of noise. In the case of averaging of MUAP trains, however, the presence of distorted potentials, interfering potentials from other motor units, baseline wander and noise can result in severe degradation in the extracted waveform.

Median averaging (MA) (Borda and Frost, 1968; Sörmo and Lagunas, 2005) is a general approach for waveform smoothing; it is recommended in cases when the statistical distributions of the amplitudes of the potentials are asymmetrical (Fox and Dalebout, 2002), particularly when spurious peaks may appear scattered within the trains of potentials. MA has been employed for MUAP waveform extraction for three decades (Antoni, 1983; Nandedkar et al., 1995), alleviating the inconvenience resulting from interfering potentials from other motor units. However, median averaging is known to yield ragged waveforms (high frequency noise) (Leonowicz et al., 2005), which might hamper the posterior measurement of MUAP waveform parameters, in particular, the number of turns.

Two other averaging techniques – closely related to EA and MA – were proposed back in the 1980s, when computing and signal processing began to be incorporated into EMG analysis and on-line procedures were the standard. *Split-sweep averaging* (SSA) (Stålberg and Antoni, 1983) splits the train of MUAPs into two sets, with even and odd potentials. Averaging is performed to each of these sets independently, and, when sufficiently close, the resulting potentials are averaged and the process stops. In fact, this is an on-line version of EA in which the number of potentials in the MUAP train is determined by the algorithm itself. The extracted waveform usually suffers corruption from noise and other MUAP interference, and so a variation, *Split-sweep median averaging* (SSMA), was introduced in which the average within each set was substituted by the median (Antoni, 1983). A template matching approach (TMA) was also put forward (Nandedkar and Sanders, 1989), in which the three most similar potentials from the MUAP train are selected and averaged to create the representative waveform. In the above-referenced paper by Nandedkar, EA, MA and TMA were compared with SSMA, which was taken as the gold standard technique. Several MUAP waveform parameters were considered for the analysis. While all techniques gave similar results in terms of amplitude, area and area/amplitude ratio, they differed noticeably in MUAP duration and number of turns and phases. Not surprisingly, the median technique provided values closer to those of the gold standard than the other two methods did. The authors concluded that both median-based approaches were more robust against noise and spurious potentials than the other two methods.

Another averaging technique rather similar to the above ones was developed by Stålberg and coworkers and introduced in their *MultiMUP* EMG analysis system (Stålberg et al., 1995). For each time point, the mean and the standard deviation of the samples of all the potentials in the train are calculated. All samples that differ from the mean by less than the standard deviation are

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