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A wavelet based method for electrical stimulation artifacts removal in electromyogram

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ABSTRACT

A technique for artifact removal based on the continuous wavelet transform is presented. It uses common mother wavelets to find the temporal localization of stimulation artifacts on electromyogram signal recording during an electrical surface evoked contraction of a muscle. This method is applied with different kinds of stimulation pulse parameters including shape and duration changes. This method is used with standard stimulation pulse waveforms such as monophasic or biphasic ones. It can also be applied when the artifacts and M waves are in the same range of amplitude where threshold techniques are inefficient. Lastly, a method to determine which mother wavelet efficiently removed artifacts is proposed, results indicate the Haar wavelet performs best among fourteen tested wavelets.

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1. Introduction

The Electromyogram (EMG) captures the electrical response of the muscle over its contraction whether muscular contraction is voluntarily or electrically induced. During a myo-electrical stimulation (ES), EMG contains two major sources. The first one is the muscular electrical activity generated by the stimulated muscle due to the contractions of muscular fibers. Sometimes, EMG also records the electrical activities of adjacent muscles which can be recruited with the same electrical stimulation [1]. It is a useful signal to study physiological characteristics of muscles over a contraction, especially in case of muscular or neurological diseases [2,3]. The second source is composed of electrical stimulation artifacts [4] which disturb the study of electrical muscular activities. In order to properly analyze the EMG signal, stimulation artifacts need to be removed [5,6]. Several techniques are already used to attenuate the impact of artifacts on EMG signals. These techniques can be split in two categories which are hardware or computation processing.

1.1. Hardware

These techniques are often implemented with respect to EMG electrodes and differential amplifier circuitry design. To cite some of them:

- Analog filtering methods are designed to remove high frequencies of EMG which contain artifacts. However, it is very difficult to filter artifacts without modifying M waves. For instance, an 8th order Chebyshev low pass filter with a 550 Hz cutoff frequency has been implemented by Solomonow et al. [7] to remove artifacts. However, these types of filters allow passage of low frequency artifacts and may also remove parts of M waves residing in the same frequency range of artifacts [8].
- Methods based on hardware amplifier gain utilized by Roskar and Roskar [9] set amplifier gains to obtain a unit gain during electrical stimulation pulses and a gain of 1000 elsewhere. However, a gain of 1000 insufficiently eliminates major artifacts [5] and lacks robustness to adapt to changes in electrical stimulation applied to magnitude or frequency.
- Blanking hardware methods consist of disconnecting (electrical isolation) EMG electrodes from the muscle during electrical stimulation. Generally, a triggering synchronization from the electrical stimulator is used [10–12]. The drawback of this technique is that the blanking window is fixed and can lead to residual artifacts if the blanking duration is too short or can lead to unintended removal of M waves when the blanking duration is too long.
- Other hardware methods can be mixed such as those implemented by Nikolic et al. [13] who use blanking and filtering at the same time.

1.2. Computation processing

Some techniques are implemented in software with computation processing as a pre-processing of EMG signal. Here, we briefly

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discuss methods using recordings of the stimulation artifact signal in order to subtract it from the EMG. Three main techniques exist to record an estimation of the stimulation artifact signal: a stimulation below the muscular contraction threshold (stimulation that does not cause any muscle contraction), a record far away from the EMG electrodes placement [1] (a second EMG is collected away from the first one to acquire pure artifacts) and a dual pulse stimulation (a second stimulation pulse is done during the refractory period which does not create any evoked signal, only the stimulus artifact is recorded) [14]. These techniques may be unable to remove all artifacts and tend to degrade the signal to noise ratio (SNR). In addition, the recorded artifact must be very accurate for a better removal process [15], which often requires supplementary hardware.

In methods based on threshold detection [16], stimulation artifacts are mostly higher than M wave amplitude by a factor of 2 or 3 [5]. This difference in magnitude is then used to distinguish between the artifact and the M wave parts. Nevertheless, it may not be suitable to specific stimulation for which the amplitude of M waves and artifacts are close.

Other mathematical methods can estimate stimulation artifacts, like curves fitting or artifact models, in order to remove them [17–19].

Possible drawbacks of the hardware technique is that it requires knowledge of when stimulations are sent to the muscle, which is the case for both amplifier gain and blanking methods. Therefore, those techniques cannot be used when electrical stimulators are not adapted. In addition, the operating window is fixed and lead to partial artifact interference. Regarding the filtering methods, they can easily be implemented in a software processing scheme without need of additional hardware circuitry. Filtering methods can also attenuate artifacts parts which merge with M waves. However, the use of filtering techniques do not guarantee artifacts are removed without modifying the M waves, which may cause a miscomputation of physiological muscle features [20]. The disadvantage of software methods using threshold techniques is the difficult determination of the threshold, especially when artifacts are in the same amplitude range of the M waves [16].

In this context, we propose a new method to remove stimulation artifacts from EMG during a rehabilitation process with an electrical stimulation by using a continuous wavelet transform (CWT) and a histogram representation. CWT is a useful tool for biomedical signal processing [21]. The aim is to find the time localization of both artifact and M waves in the CWT domain in order to erase artifacts. The threshold is automatically found to avoid aforementioned difficulties from manual selection uncertain manually choice. We show that even when the amplitudes of artifacts and M waves are equivalent, CWT domain analysis can provide a suitable separation between them. To present the removal method, the Haar mother wavelet is used. In order to check flexibility of our approach we test different but common stimulation pulse shapes, which are monophasic, biphasic and dual biphasic, and different stimulation pulse durations. Indeed, when the stimulation changes in its shape, the artifact and the M wave evolved [22] such that the presented artifact removal approach was not impaired with these modifications. Next, results obtained with a panel of other mother wavelets are displayed, leading to selection of the most promising decomposition. Lastly, two indexes were proposed showing that the Haar wavelet best distinguished artifacts and M waves apart.

2. Materials and methods

2.1. Data set recording

The material used for our experiments delivered the electrical stimulation and performed EMG signal acquisition in real time [23]. The electrical stimulator generated controlled current pulses and constant stimulation with a maximum of ±100 mA for a body impedance of 1.5 KΩ between the two stimulation electrodes, a frequency pulse train from 10 Hz to 100 Hz and a pulse duration from 0.5 ms to 2 ms for 5 different pulse shapes most common in the literature (monophasic, biphasic, dual biphasic, absorbed biphasic and N-let). The EMG amplifier recorded EMG from muscle during the stimulation with bipolar electrodes and a reference electrode. Instrumentation amplifiers used for the circuit included the INA128 from Texas Instruments with a 120 dB of Common Mode Rejection Ratio for a removal of common voltage from bipolar electrodes with a high input impedance (>1GΩ). The M waves extracted from the global EMG signal during evoked contractions were used to estimate the fatigue level of the muscle during the rehabilitation session [24]. The EMG signal was saved with a sample rate of 10 kHz. A dedicated software allowed management of stimulation parameters and analysis of muscular fatigue level following artifact pre-processing software among three methods: blanking, thresholding algorithm or the method proposed in this study.

All experiments were carried out on the right biceps muscle in an isometric position where the skeleton remained fixed. Subjects were placed in a Biodex pro 3 device [25] to be sure that the isometric position, carried on throughout the contraction, was maintained. The experiments were carried out on five subjects (mean 24 ± 2 years) with bipolar (10 mm disk Ag/AgCl from Nessler) electrodes with liquid conductor gel. Electrodes were placed over the target muscle belly, parallel with the muscles fibers (tendon to tendon axis). Electrode placement was compliant with EMG processing standard [26]. Ten different kinds of stimulation were performed on each subject including variation in amplitude, frequency, pulse duration and form shape of the stimulation parameters. Each stimulation train was six seconds long. Our experiments provided a data base of fifty samples of EMG signals.

2.2. Artifacts removal process

We propose a method based on the continuous wavelet transform to detect and remove the stimulation artifacts contained in the EMG. The idea is to use a standard mother wavelet, such as the Haar wavelet, and to vary the scale factor of the continuous wavelet transform to determine which scale factor provides maximum correlation between the stimulation artifact and the wavelet coefficient. Nevertheless, the treatment should leave unchanged the M waves contained in stimulation artifacts in order to allow the extraction of physiological muscle state parameters present in M waves, such as muscular fatigue level.

In order to initialize the artifact removal process, the CWT uses the Haar wavelet. Then, tests are performed with different kinds of artifacts shapes. Next, other standard mother wavelets were applied in the CWT such as Daubechies or Symlets.

2.2.1. Best scale factor determination

The Haar wavelet has the characteristic to look like the stimulation artifacts in the sense that the artifact has a rectangular shape (rising and falling sharp edges), due to the amplifier saturation, as the Haar mother wavelet. This wavelet therefore might properly detect artifacts. However, the scale factor of Haar wavelet which best fit the artifact pattern has yet to be determined. To find it, the continuous wavelet transform was applied between EMG with artifacts named V_{EMG} and a wavelet ψ (Haar wavelet) undergoing a scale factor a, such that

$$C_{a,b}(V_{EMG}(t), \psi(t)) = \int_{-\infty}^{\infty} V_{EMG}(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt, \quad (1)$$

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