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Artifact cancellation using median filter, moving average filter, and fractional derivatives in biomedical signals

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Abstract

We present comparison of median, and moving average filters for cancellation of electrocardiographic artifacts in electromyography signals recorded on the chest and the neck of a subject. For appropriate diagnostic decree, the artifact cancellation is crucial in electrophysiological recordings. Trunk, chest and neck muscles are most vulnerable to electrocardiographic artifacts due to heart or large blood vessels proximity to the recording location. We recorded signals from two muscles in order to evaluate the procedure for adequate filter selection and filter parameters adjustment. The filter's performance, evaluated by crest factor is presented for both median, and moving average filters. Additionally, the performance of median filter is evaluated for prior fractional derivation of recorded signal. The results indicate that the median filter in combination with fractional derivation can be used for electrocardiographic artifact cancellation in electromyographic recordings. Potential application of this processing procedure includes muscle assessment in patients with neurological disorders.

Key words: EMG, ECG noise, median filter, MA filter, fractional derivative

1. Introduction

Surface electromyographic (sEMG) signals are electrical signals formed by electrical activity of muscles. Muscle’s electrical activity can be recorded by surface Ag / AgCl electrodes placed on skin surface over the bulk of the muscle of interest [1].

Amplitude of raw sEMG signal is up to 0.5 mV, and typical frequency range of signal is between 6 Hz and 500 Hz, showing most frequency power between 20 Hz and 150 Hz. sEMG signals are recorded with differential amplifiers with preferably CMRR (common mode rejection ratio) higher than 95 dB [2]. In order to reduce cable movement artifacts, preferred recording technique is application of relatively small pre-amplifiers in proximity to the detection site. The main advantage of such pre-amplifier is artifact reduction due to early pick up of the signal [1].

sEMG signal achieved during muscle contraction may reflect the level of the muscle activity. Its non-invasive nature makes sEMG valuable and safe method for estimating the level of muscle contraction. However, contamination by nearby sEMG signals known as *cross-talk* may influence the validity of the signal. sEMG signals are crucial in assessment of muscular performance, treatment, and training regimes in patients with muscular and neurological pathologies [1, 3-4]. For appropriate application of sEMG signal in medical practice, its noise reduction, and preferably complete noise cancellation are critical.

There are several internal, and external factors that influence characteristics of recorded sEMG signal. Tissue types, and tissue thickness overlaying muscles can induce baseline noise. Artifacts can occur as a consequence of changes in geometry between signal origin site and electrodes position. As this signal has relatively low amplitude (~ 0.5 mV), the direct interference of power hum is present [1]. Unwanted biological artifacts with proximate origin to recorded muscle of interest can also be present, and often cannot be avoided.

ECG (electrocardiography) signal can be contaminated with sEMG signals measured from trunk, chest, and neck muscles. These muscles are most vulnerable to ECG artifacts due to heart and large blood vessels proximity to the sEMG recording location. Spectrums of ECG (0.05 – 100 Hz), and sEMG (6 - 500 Hz) signals are overlapped, and depending on the detection site, the sEMG recording can have various ranges of SNR (signal to noise ratio). Several methods for cancellation of ECG artifact were presented. Joint use of Independent Component Analysis (ICA), and discrete wavelet transform was used in order to extract ECG signal component and to subsequently remove it [5]. However, it has been shown that this method has limited performance, and cannot be applied in some cases [5].

Practically, some researchers use electrodes replacement in order to avoid or to decrease ECG interference during sEMG recording of trunk, chest, and neck muscles [6]. However, this is not an optimal solution since the electrodes position for sEMG recording should be along the muscle fibers, and over the bulk of muscle belly [2].

Large number of motor units are responsible for muscle activation causing short-time fluctuations in pattern of sEMG signal. This pattern cannot be exactly reproduced by its identical shape for repeated measurements [1]. Nevertheless, the repeated shape of sEMG activation is present during repeated measurements. This shape termed sEMG envelope is most commonly used for various sEMG application. Two main smoothing techniques for sEMG envelope calculation are moving average (MA) filter, and root mean square (RMS) based smoothing method [1].

MA filter is based on application of defined time window. For each window width in seconds, the central sample is replaced by the average of sample values in window. This is a type of finite impulse response filter. It is often used as a smoothing technique in biological signals, with window size between 50 ms and 100 ms [1]. In this paper, we applied MA filter on recorded sEMG signal on chest and neck, and compared its operation to nonlinear median filter.

Median filter is commonly used nonlinear filter for digital image processing [7]. When applied in biological signals, it is used in one-dimensional form. This filter consists of a sliding time window. The central sample of each time window is replaced by the median of sample values in window. This filter is mainly used when value of the signal have sudden changes [8].

The hypothesis for application of MA filter was that the time-domain filter would provide smooth envelope of sEMG signal and at the same time filtering of ECG artifact. We compared MA filter performance to median filter performance for envelope calculation, in order to test the suppression of sudden changes (ECG peaks) in sEMG signal.

In order to increase sudden changes suppression in sEMG signal, we additionally performed fractional derivation of sEMG signal prior to median filtering. Artifact removal was observed for median filter application with and without prior fractional derivation.

Fractional derivative is an extension of ordinary derivative, and it enables derivative calculation of non-integer values [9-10]. Important difference between integer-order derivative and fractional-order derivative is that the slope of the amplitude characteristic of the integer-order derivative is always an integer multiple of the 20 dB/decade, which is not case with fractional-order derivative [9]. Fractional calculus is applied widely in physics and engineering, mainly in the modeling of different systems [9,11-18]. Application of fractional calculus has been presented for development of fractional multi-models of muscles [16-18]. The application of multi-models decreased number of parameters required for modeling muscle contraction, and enabled future implementation on an embedded system [16-18].

Main aim of this study was to apply relatively simple MA filter, and to compare its performance to nonlinear median filter with and without application of fractional derivation in order to detect repeated shape of sEMG signal termed envelope, and to concurrently provide ECG noise cancellation. Briefly, in this paper, we compared three different methods for ECG noise removal, and sEMG envelope calculation: 1) MA filter, 2) median filter applied on sEMG signal, and 3) median filter applied on fractional derivative of sEMG signal. We recorded sEMG signals on two muscles in healthy subject during muscle relaxation and contraction. Sensitivity of each algorithm to window width of MA, and median filters is presented by crest factor. The crest factor was chosen in order to assess the presence of sudden changes (ECG spikes) in sEMG signal. Additionally, we presented crest factor based analysis for selection of order of fractional derivative in combination with nonlinear median filter.

2. Methods and materials

A. *Acquisition set-up and protocol*

We recorded surface electromyography (sEMG) signals from *pectoralis major* and *sternocleido mastoideus* muscles on the left side in one healthy subject. EMG electrodes were placed according to SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) protocol [2]. The reference electrode was placed over *clavicle* bone. Signals were acquired using Biovision preamplifiers (Biovision Ltd., Wehreim, Germany) with gain set to 1000. sEMG signals were digitized with NI USB 6212 A / D converter (National Instruments Inc., Austin, USA) with sampling rate of 1000 samples per second, and 16 bits resolution.

Two trials were recorded for each muscle with approximate duration of 15 s in the sitting position. During first trial, subject was instructed to relax muscles, and during second trial subject was instructed to contract muscles (at self chosen strength) for 3-5 times. Each contraction lasted no more than 7 s.

Subject (female, 30 years, 176 cm height, 73 kg weight) signed an Informed Consent approved by the Local Ethic Committee, according to Helsinki declaration.

B. *Signal preprocessing*

All preprocessing and processing steps were implemented in MATLAB R2013a (The Mathworks, Natick, MA, USA).

In order to reduce movement artifacts, we filtered sEMG signal with high-pass 3rd order Butterworth filter with cutoff frequency set at 10 Hz, and in order to reduce power noise, we used notch filter (50 Hz). For further processing, filtered signals were rectified.

Fig. 1 illustrates the sEMG signal preprocessing steps consisting of filtering and rectification. The first panel (a) in Fig. 1 shows raw sEMG signal – one contraction of the *pectoralis major* muscle. ECG noise is visible in Fig. 1. (a), and peaks correspond to pulse rate present R waves in standard ECG waveform. The second panel (b) in Fig. 1 shows sEMG signal after offset, and power noise removal. The third panel (c) in Fig. 1 shows the rectified sEMG signal.

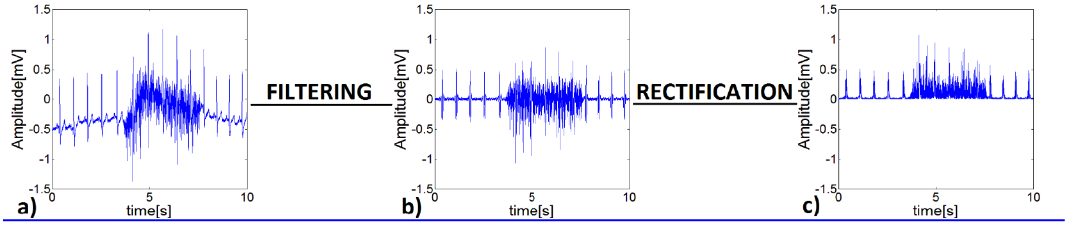

Figure 1. Diagram of sEMG signal preprocessing steps: (a) Recorded raw sEMG signal from *pectoralis major* muscle during contraction (approximate duration 4-8 s); (b) sEMG signal after filtering with high pass and notch filter for noise reduction; (c) Filtered sEMG signal after rectification.

C. *Median filter*

In order to extract sEMG envelope, and to perform ECG cancellation, we applied one dimensional median filter on rectified signal. We applied median filter for various window widths ranging from 10 ms to 2000 ms with step of 10 ms. This filter was applied in all recorded trials of sEMG signal.

Fig. 2 illustrates the application of median filter on preprocessed sEMG signal from Fig. 1. The first panel (a) in Fig. 2 shows the preprocessed sEMG signal. The second panel (b) in Fig. 2 shows sEMG signal after application of median filter with window size of 500 ms. The third panel (c) shows the sEMG signal after application of median filter with window size of 1000 ms. The fourth panel (d) in Fig. 2 shows the sEMG signal after application of median filter with window size of 2000 ms. All envelopes are presented in Fig. 2 with compensated delay that equals window size.

D. *MA filter*

On preprocessed sEMG signals, we applied MA filter in order to obtain sEMG envelope and to reduce ECG artifacts. In order to analyze window width influence on ECG cancellation, we applied MA filter with window widths from 10 ms to 1000 ms with step of 10 ms in all recorded trials of sEMG signal.

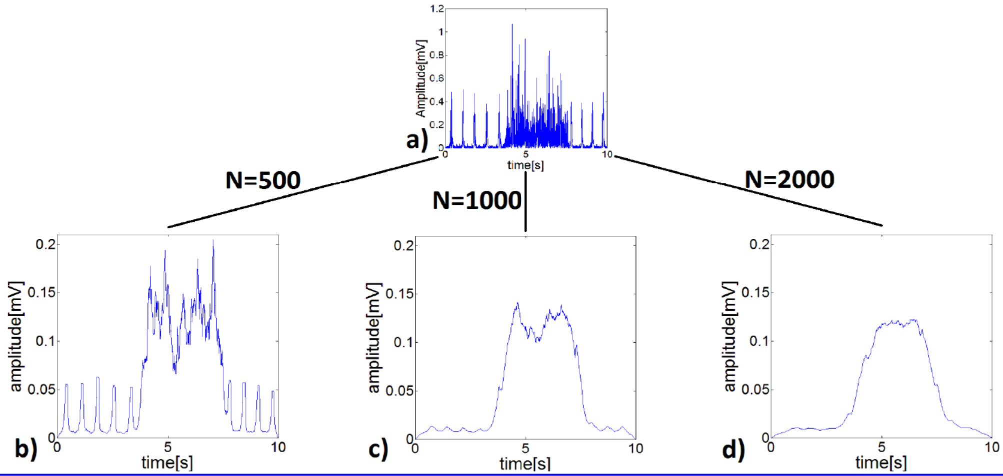

Figure 2. Diagram of the application of median filter: (a) Preprocessed sEMG signal; (b) Preprocessed sEMG signal after application of median filter with window size of 500 ms; (c) Preprocessed sEMG signal after application of median filter with window size of 1000 ms; (d) Preprocessed sEMG signal after application of median filter with window size of 2000 ms. N stands for window length.

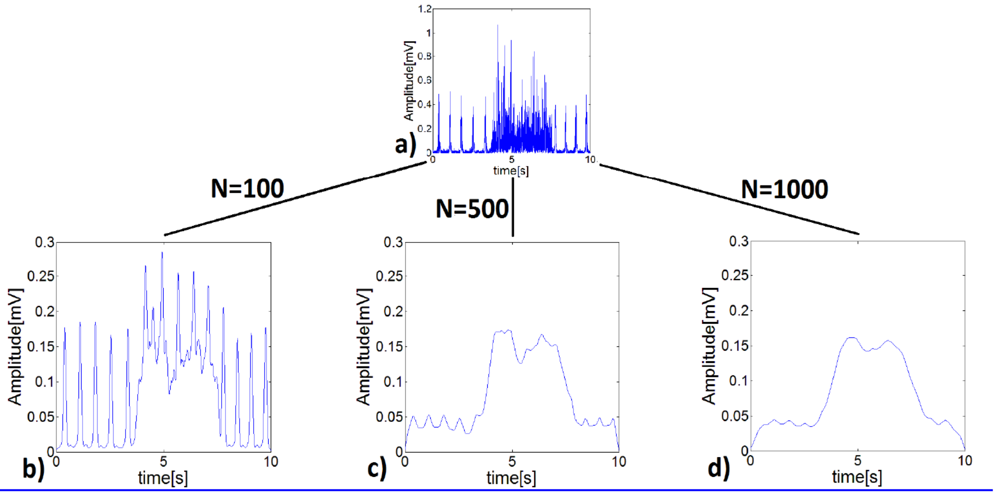

Figure 3. Diagram of the application of moving average (MA) filter: (a) Preprocessed sEMG signal; (b) preprocessed sEMG signal after application of moving average filter with window size of 100 ms; (c) preprocessed sEMG signal after application of moving average filter with window size of 500 ms; (d) preprocessed sEMG signal after application of moving average filter with window size of 1000 ms. N stands for window length.

Fig. 3 illustrates the application of MA filter on preprocessed sEMG signal presented in Fig. 1. The first panel (a) in Fig. 3 shows the preprocessed sEMG signal. The second panel (b) in Fig. 3 shows sEMG signal after application of MA filter with window size of 100 ms. The third panel (c) in Fig. 3 shows the sEMG signal after application of MA filter with window size of 500 ms. The fourth panel (d) in Fig. 3 shows the sEMG signal after application of MA filter with window size of 1000 ms. sEMG envelopes are presented in Fig. 3 with compensated delay that equals window size.

E. *Evaluation of artifact cancellation*

Quantitative evaluation of application of median, and MA filters for ECG noise reduction, and envelope calculation of sEMG signals is done by crest factor. The crest factor is calculated as ratio of peak amplitude and RMS value of sEMG signal. Crest factor was calculated for all recorded trials, and for all window widths.

F. *Fractional derivative*

Additionally, in order to increase SNR in signal filtered with median filter, fractional derivative of 0.3, 0.6, and 0.9 orders was applied on the preprocessed signal before application of median filter. Quantitative analysis of this method was also done using crest factor.

MATLAB function used for fractional derivative calculation *fderiv* was downloaded, and implemented from [10]. This function has input parameters: signal, fractional order, memory parameter, and sampling rate. For memory parameter, we used default recommended size of 1, in order to reduce the number of samples taken into account for fractional derivative calculation - "short memory principle" [9-10]. The fractional derivative is in *fderiv* function implemented using Grunwald-Letnikov fractional derivative. The generalized form of Grunwald-Letnikov fractional derivative is presented in Equation (1).

$$d^{\alpha} f(x) = \lim_{h \to 0} \frac{1}{h^{\alpha}} \sum_{m=0}^{\frac{t-a}{h}} (-1)^m \frac{\Gamma(\alpha+1)}{m!\,\Gamma(\alpha-m+1)} f(x-mh) \tag{1}$$

In Equation (1) $\Gamma(\cdot)$ is gamma function, t and a are upper and lower limits, respectively, α is the order of fractional derivative of function $f(x)$ labeled as $d^{\alpha} f(x)$, and h is the sampling period.

3. Results

Crest factors in function of a window size, calculated for sEMG signals after application of median, and MA filters are shown in Fig. 4. a), and Fig. 4. b), respectively. The values are calculated for signals recorded during relaxation and contraction of muscles *pectoralis major*, and *sternocleido mastoideus*.

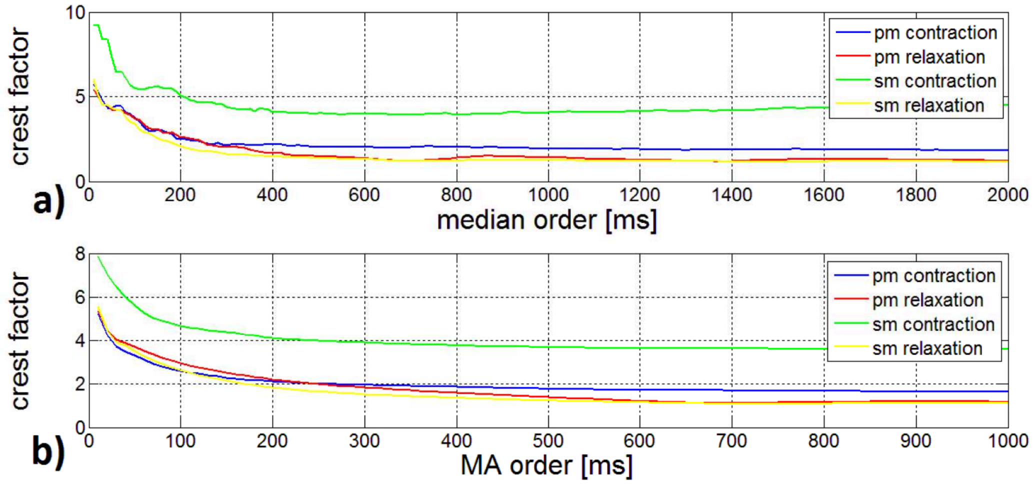

Figure 4. Crest factor diagrams: (a) Crest factors for four sEMG envelopes obtained by application of median filter for window widths 10-1000 ms; (b) Crest factors for four sEMG envelopes obtained by application of MA filter for window widths 10-1000 ms. Abbreviations pm and sm stand for *pectoralis major*, and *sternocleido mastoideus* muscles.

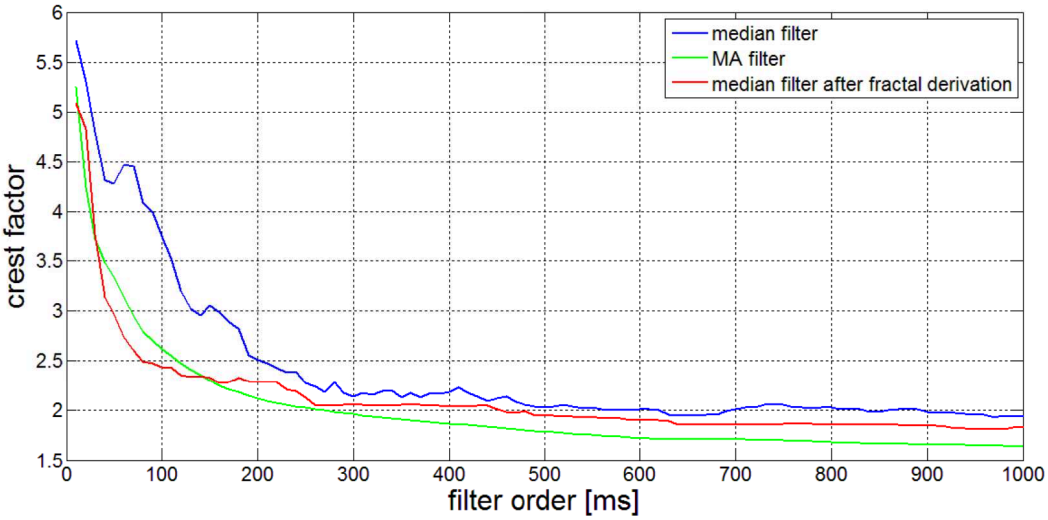

Figure 5. Crest factors for window widths from 10 ms to 1000 ms for signals recorded on *pectoralis major* muscle during contraction. Curvatures present crest factors after application of median filter, moving average filter, and median filter applied on fractional derivative of sEMG signal (order 0.9).

Values of crest factor for various window widths of median filter, MA filter, and median filter applied on fractional derivative of sEMG signals recorded on *pectoralis major* muscle during contraction are shown in Fig. 5.

Crest factor values for various window widths of median filter applied on fractional derivative (three different orders) of sEMG signals recorded on *pectoralis major* muscle during contraction are shown in Fig. 6.

Preprocessed sEMG signal recorded on *pectoralis major* muscle, and its envelopes obtained after application of median filter with window size of 500 ms, and MA filter with window size of 700 ms are shown in Fig. 7.

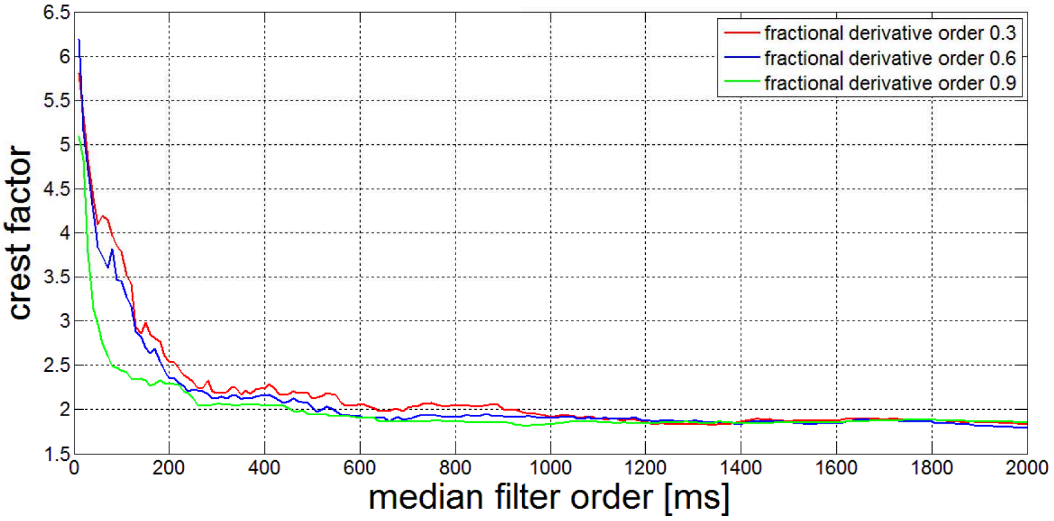

Figure 6. Crest factors for window widths from 10 ms to 2000 ms for signals recorded on *pectoralis major* muscle during contraction. Curvatures present crest factors after application of median filter applied on fractional derivatives of sEMG signal calculated with three different orders (0.3, 0.6, 0.9).

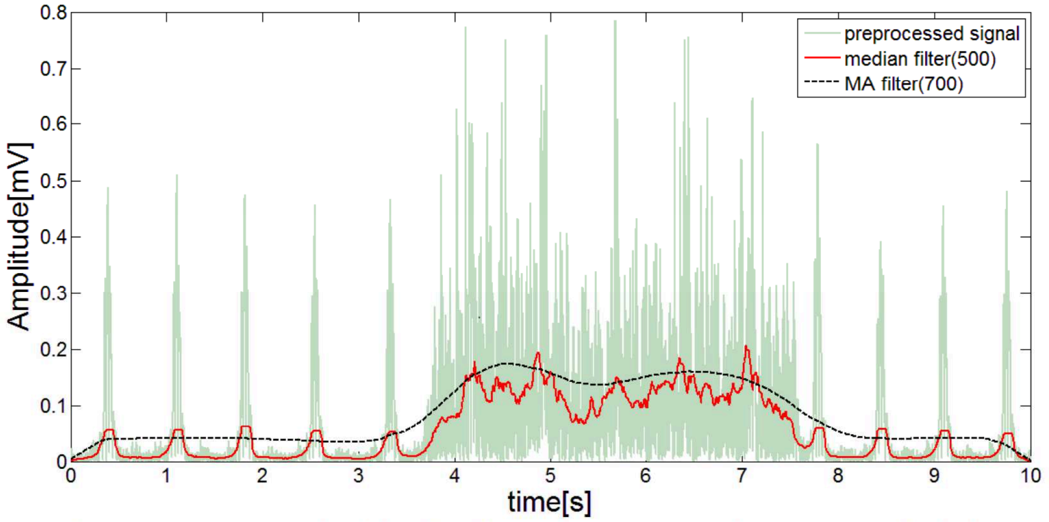

Figure 7. Preprocessed sEMG signal recorded on *pectoralis major* muscle during contraction, and its envelopes obtained with application of median filter with window size of 500 ms, and MA filter with window size of 700 ms.

4. Discussion

Crest factor curvature is similar in all four trials of recorded sEMG signals after application of median filter (Fig. 4). Higher crest factors are observed in Fig. 4 in envelopes obtained from sEMG signals recorded from *sternocleido mastoideus* muscle during muscle activation. By additional inspection of recorded sEMG signals, we determined the source of larger crest factors. Subject performed three higher muscle contractions with approximately 2.5 higher sEMG amplitude levels than other two contraction. In order to avoid influence of task performance on crest factor further research should include:

A. muscle contraction onset and offset detection, and consecutively crest factor evaluation during specified sEMG amplitude levels, and
B. evaluation of the proposed methods for ECG cancellation on data created by superimposing artifact free real-life sEMG signals with synthetic ECG.

As a consequence, all crest factors calculated for sEMG signals recorded during muscle contraction had higher values compared to crest factors calculated for sEMG signals recorded during muscle relaxation (Fig. 4).

When MA filter was applied, crest factors were smaller compared to crest factor calculated for median filter application (Fig. 5) for all window widths. This showed decreased ECG artifact performance for MA application compared with median filter performance. Crest factor values for window widths lower than 200 ms are much higher for median filter compared to values for window widths higher than 200 ms. However, after intermediate step with fractional derivation, crest factor values for window widths lower than 200 ms are drastically reduced compared to median, and MA filters application (Fig. 5).

Curves of crest factor values that are shown in Fig 6. were used to compare different orders of fractional derivative in intermediate step. Crest factor values for window widths lower than 200 ms are much lower for highest fractional derivative order (0,9) then for the other two, and for window widths higher than 200 ms there is no significant difference. In this case high fractional order close to 1 as intermediate step gives best results.

In Fig. 7, sEMG envelopes obtained by application of median, and MA filters with optimal sizes of the windows that showed minimal crest factor in Fig. 4 (500 ms for median, and 700 ms for MA) are presented. Smoother envelope is a result of MA filter application (Fig. 7). It should be emphasized that though it is practical to compare cancellation techniques for various window widths, the dynamical properties of sEMG signals are subject to change. The recommended MA window size is 50-100 ms for most sEMG applications [7].

Crest factors of sEMG envelopes obtained by median filter after fractional derivation (order 0.9) for window widths of 50 ms, 70 ms, and 100 ms are 2.96, 2.60, and 2.44, respectively. On the other side, crest factors of fractional derivative of sEMG envelopes obtained by MA filter for window widths of 50 ms, 70 ms, and 100 ms are 2.33, 2.95, and 2.62, respectively. This indicates that fractional derivative decreases amplitudes of ECG peaks in sEMG envelopes obtained with median filter application and fractional derivative in combination.

Limitations of this study are:

A. We did not check the artifact cancellation for various orders (with step lower than 0.3) of fractional derivatives, and future study should include the optimal fractional derivative calculation in a more precise manner.
B. We did not perform fractional derivation prior to MA filter application, and future studies should incorporate this technique combination.
C. Future study should include verification of the proposed method in other biological signals, such as electroencephalographic signals [5, 19].

Future work should include larger healthy sample for appropriate evaluation of the proposed method, and statistical verification. Additional verification of presented method is needed in clinical setting.

sEMG signals recorded in patients with neurological disorders may have different SNR, and time window width, and fractional derivative optimization should be provided for successful clinical application.

5. Conclusions

The results presented in this paper indicate the potential application of fractional derivative of order 0.9, and median filter for ECG artifact cancellation in sEMG signals recorded from chest, neck, and trunk muscles. Presented procedure should be tested in larger healthy sample and in clinical setting for an appropriate evaluation. Main disadvantage of the presented method is that the procedure cannot be entirely implemented for real-time processing, due to delays. Nevertheless, the potential practical implementation of this method for offline muscle assessment in patients with neurological disorders should be further tested.

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