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Efficient procedure to remove ECG from sEMG with limited deteriorations: Extraction, quasi-periodic detection and cancellation

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ABSTRACT

The interpretations of the surface electromyography (sEMG) signals from the trunk region are strongly distorted by the heart activity (ECG), especially in case of low-amplitude EMG responses analyses. Many methods have been investigated to resolve this nontrivial problem, by using advanced data processing on the overall sEMG recorded signal. However, if they reduce ECG artifacts, those cancellation methods also deteriorate noiseless parts of the signal. This work proposes an original ECG cancellation method designed to limit the deterioration of sEMG information. To do that, the proposed techniques does not directly attempt to remove the ECG, but is based on two main steps: the localization of ECG and the cancellation of ECG but only where heart pulses have been detected. The phase of localization efficiently extracts the ECG contribution by combining the discrete wavelet transforms (DWT) and the method of independent component analysis (ICA). And finally, this phase takes advantage of quasi-periodic properties of ECG signals to accurately detect pulses localization with an original algorithm based on the fast Fourier transform (FFT). Intensive simulations were achieved in terms of relative errors, coherence and accuracy for different levels of ECG interference. And the correlation coefficients computed from the paraspinal muscles EMG signals of 12 healthy participants were also used to evaluate the developed method. The results from simulation and real data demonstrate that the proposed method accurately detects pulses positions and efficiently removes the ECG from EMG signals, even when both signals are strongly overlapped, and greatly limits the deterioration of the EMG.

1. Introduction

Non-invasive and inexpensive, surface electromyography (sEMG) is an effective method that has been widely adopted in clinical and research works to study topics related to muscular activities such as neuromuscular diseases. Surface EMG electrodes provide a non-stationary electrical signal representing the sum of subcutaneous motor unit action potentials generated during a muscular contraction. However, before any interpretations of the obtained signals, post-processing is needed. Indeed, sEMG electrodes are very sensitive elements, and many artifact sources can corrupt the recorded signal: movement artifacts, interferences from power lines, others devices, or others body parts. Artifacts cancellation is a key topic in biomedical signal processing.

When a muscular activity is recorded in the thoracic or trunk region, the sEMG signals are strongly contaminated by the heart muscles electrical activity (ECG – electrocardiogram). In this case, it is difficult to separate the heart contribution from the muscular one, because their frequency spectra overlap: (i) from 10 to 500 Hz with most power between 20–200 Hz for EMG and (ii) from 0 to 100 Hz for ECG with a power failing after 35 Hz [1]. Cardiac artifacts clearly corrupt muscular responses. This corruption is more damaging if the signals to analyse are low muscular activities, as for example, it is the case in studies about the impacts of the spinal manipulation therapy on the human physiologic responses [2–4]. In those experimentations, sEMG electrodes recorded spine erector spinae muscles (close to thoracic vertebrae) obtained during spinal manipulation realized by a servo-controlled motor [2]. Those sEMG sensors responses are low-amplitude signals and are strongly contaminated by cardiac pulses, because of their position. To address this situation, the present paper attempts to propose an effective algorithm to remove the ECG, while maintaining the maximum information from targeted muscles.

Due to the biomedical engineering community interest, many methods to remove ECG from EMG signals have been proposed in the literature as exposed in [5,6]. Simple high-pass filters used in

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[1,7] do not represent an acceptable solution to reach this study's objective: EMG information is too much deteriorated. Based on an additional electrode, which records only ECG, the adaptive noise canceller (ANC) structure presents a powerful solution to remove ECG from EMG signal. This method has been used from respiratory and trapezius muscles in [8,9], both with RLS (Recursive Least Square) [10]. Authors in [11] propose a modified version of FBLMS (Fast Block Least Mean Squares) to adjust the filter coefficients of ANC, which returns better performance to cancel ECG than RLS. However, ANC performances are sensitive to synchronisation between the ECG contribution from both electrodes (sEMG and ECG reference electrodes) and are often weak in case of real signals. As the ANC method, the adaptive line enhancer (ALE) [12] is a structure based on adaptive filtering, which does not require a reference signal to remove ECG from EMG as in [13,14]. This technique allows to efficiently remove signal noise and to separate periodic or quasi-periodic narrowband components from a wideband Gaussian signal. Nevertheless, ALE cannot perform if the noise is not white Gaussian [13], and it can also remove periodic or quasi-periodic parts of desired EMG signal.

Independent Component Analysis (ICA) [15] and Singular Spectrum Analysis (SSA) [16], two methods of blind sources separation, have been also used to substrate ECG from sEMG electrodes. Based on several sEMG electrodes, some methods use ICA to first decompose EMG signals into statistically independent components. Then, the components containing ECG are discarded and remaining components are used to construct cleaned signals. In [17], ICA components corresponding to ECG were determined using the periodic characteristics of cardiac pulses (RR interval). This process was applied on trunk, spinal lumbar and diaphragm muscles in [17–21]. However, ECG and EMG contributions are not perfectly separated with ICA, and, when ECG components are totally removed, EMG substantial values are lost. This deterioration is minimized by authors in [15,22]. They use a high-pass filter at 30 Hz cut-off frequency on ECG components before reconstructing signals. Contrary to ICA, based on several sEMG electrodes, SSA method uses several delayed versions of a single signal to extract independent components [15]. A technique based on SSA to determine and cancel the ECG contribution of the signal was presented in [14,23,24]. It outperforms the ALE [14], but some errors occur when the periodic signal (ECG) is not narrowband or well defined [13]. In order to overcome this problem, a combination of SSA and ALE was suggested in [13] and improved in [25], in which the ALE structure selects adaptively the ECG component for wideband periodic signals disturbed by non-Gaussian noise. As classic ALE, this method can deteriorate EMG by removing its periodic components.

Widely applied in bio-signals processing such as events detection [26], classification [27] or artifacts cancellation, wavelet transform (WT) is a powerful time-frequency approach [28,29]. However, WT degrades EMG when it is directly used to remove ECG. Better performances are obtained when the ICA method is combined to WT in order to select and cancel ECG components as proposed in [30–32]. This structure has been designed with discrete and continuous wavelet transform in [33,34].

Those techniques based on ICA and WT, like all other powerful methods exposed previously, apply their treatment along the whole signal, even during noiseless sections: they efficiently remove ECG, but greatly deteriorate the desired EMG. The preservation of the EMG contribution during the ECG cancellation is essential in this study. For this reason, the proposed method is based on a local cancellation approach. Contrary to other approaches, this method does not directly cancel the ECG; it first focuses on the ECG localization, before removing it only where pulses positions have been estimated (cancellation phase). The major contribution is the localization phase that is able to accurately locate cardiac pulses, even if the ECG and EMG amplitudes are close. First, the ECG localization realized by efficiently combining the discrete wavelet transform (DWT) and ICA to extract the ECG information from the sEMG electrodes. Then, using this extracted information, an original pulses detection based on fast Fourier transform (FFT) takes advantage of the quasi-periodic nature of the ECG to find the cardiac pulses positions with a strong accuracy. This step of the proposed method is essential to greatly remove ECG with limited EMG deteriorations. Indeed, as often wrongly assumed in literature, ICA does not perfectly separate ECG from sEMG; particularly in case of real data or when EMG and ECG contributions are closed.

The efficiency of the combination of DWT and ICA to first localize cardiac pluses and the impact of the two phases structure (localization and cancellation) to remove ECG from sEMG have been preliminary presented and evaluated in a conference paper [30]. In order to precisely describe the complete version of the proposed method (with addition of the quasi-periodic ECG pulses detection) and to realize an intensive evaluation, the present paper is organized as follows: the Section 1 describes the signals model used for simulation. Section 2 details the main parts of the proposed method for ECG cancellation: the ECG localization with extraction and detection of the cardiac signal, followed by its cancellation. A particular focus on the proposed algorithm of ECG pulses detection based on FFT is exposed in Section 3. The proposed method is then evaluated in Section 4. Intensive simulations have been achieved to determine the impact of each part of the proposed method in terms of relative errors (time-domain), coherence (frequency-domain) and accuracy of its pulses detection. Simulations were conducted for different levels of ECG interference on EMG; the results obtained by methods based on classic filtering and SSA are used for comparisons. Furthermore, in Section 5, the performances of proposed method are evaluated with real data obtained during the study of spinal manipulation effects [2–4]. Finally, some brief conclusions are drawn in Section 6.

2. Signal model

In the signal model, realized to evaluate ECG cancellation methods, K fictive closed sEMG electrodes are considered, which record muscular activities contaminated by ECG from the same source. As defined in (1) and presented in Fig. 3a, $s_k[n]$ is the sum of the muscular contribution $s_k^{\mathrm{EMG}}[n]$ (information) and the ECG component $s_k^{\mathrm{ECG}}[n]$ (interference) of each electrode. The indexes $k = 1, 2, \ldots, K$ and $n = 1, 2, \ldots, N$ are respectively referred to the electrodes and samples, with N the samples number and F_s the sampling frequency.

$$s_k[n] = s_k^{\mathrm{EMG}}[n] + s_k^{\mathrm{ECG}}[n] \quad (1)$$

The interference levels are controlled with the following SIR (Signal to Interference Ratio) expression in dB, noted r_k^{SIR} for a given sEMG electrode k:

$$r_k^{\mathrm{SIR}} = 10 \log \left(P_{s_k} / P_{s_k^{\mathrm{ECG}}} \right) \quad (2)$$

where P_{s_k} is the power of the signal $s_k[n]$ recorded by the electrode k, and $P_{s_k^{\mathrm{ECG}}}$ the power of its ECG contribution.

The simulated EMG contribution $s_k^{\mathrm{EMG}}[n]$ of $s_k[n]$ are obtained from an autoregressive modelling described in [27]. For each electrode k, the spectral content obtained from a real EMG without ECG is first inserted in a white noise with a normal distribution. Then, the obtained signals are modulated with an envelope shape which represents repeated muscle contractions (see obtained EMG signals in Fig. 1a). The same envelope shape is used for all K electrodes. Based on this process, all synthetized EMG responses are closed but different.