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An automated ECG-artifact removal method for trunk muscle surface EMG recordings

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A B S T R A C T

This study aimed at developing a method for automated electrocardiography (ECG) artifact detection and removal from trunk electromyography signals. Independent Component Analysis (ICA) method was applied to the simulated data set of ECG-corrupted surface electromyography (SEMG) signals. Independent Components (ICs) correspond to ECG artifact were then identified by an automated detection algorithm and subsequently removed. The detection performance of the algorithm was compared to that by visual inspection, while the artifact elimination performance was compared with Butterworth high pass filter at 30 Hz cutoff (BW HPF 30). The automated ECG-artifact detection algorithm successfully recognized the ECG source components in all data sets with a sensitivity of 100% and specificity of 99%. Better performance indicated by a significantly higher correlation coefficient ($p < 0.001$) with the original EMG recordings was found in the SEMG data cleaned by the ICA-based method, than that by BW HPF 30. The automated ECG-artifact removal method for trunk SEMG recordings proposed in this study was demonstrated to produce a very good detection rate and preserved essential EMG components while keeping its distortion to minimum. The automatic nature of our method has solved the problem of visual inspection by standard ICA methods and brings great clinical benefits.

1. Introduction

Surface electromyography (SEMG) recorded from trunk area is susceptible to strong interference from cardiac activities, i.e. electrocardiography (ECG) signal [1–5]. The ECG artifact constitutes a serious problem for trunk muscle SEMG measurement. It distorts the SEMG signals in both amplitude and frequency [6], compromising the accuracy and efficacy of the recorded SEMG in both clinical interpretation [6–8] and myoelectric control [9,10].

Despite efforts to reduce noise at the source via appropriate skin preparation and the use of well designed active electrodes and signal recording instrumentation, some noises will always accompany the desired signal [2,11]. The ECG artifacts, as obtained from the same electrodes as the EMG, are difficult to remove, due to considerable overlapping of the frequency spectra of these signals [12]. Several signal processing techniques for noise reduction have been proposed to eliminate ECG artifact from the SEMG signals in past studies [1,3–5,13–17]. Most of these approaches were developed based on algorithms using either the spectral filtering method or adaptive filtering technique. The spectral filtering method eliminates all the components of a selected frequency range, while the adaptive filtering technique gives clean signals by subtracting the ECG signal, obtained by an additional reference channel, from the noised SEMG signals. A recent study [4] evaluated commonly used ECG-artifact removal techniques for EMG signals suggested the use of Butterworth filter with 30 Hz cutoff (BW HPF 30) after comparing their actual performances. Nevertheless, intrinsic limitations behind the algorithms of these presented methods lead to limited success in ECG-artifact removal and unnecessary loss of SEMG components.

Independent Component Analysis (ICA) method is able to separate statistically independent source signals from a given set of their linear combinations [11,18–21]. It makes no assumption about the mixing process and requires very little information about the sources of the signals to be separated [18]. ICA method is especially valuable to remove artifacts from biomedical signals [22,23]. Unlike conventional noise elimination methods, the ICA method removes artifacts that are related not to specific frequencies but to different origins [24]. Recently, ICA-based artifact removal methods have been applied to Electroencephalography (EEG) [25–28] and Magnetoencephalography (MEG) [23,29] data for research purpose. Encouraging results have been demonstrated from these studies with an improved signal quality and corresponding clinical interpretation. However, in case of ECG-artifact removal for SEMG recordings, the efficacy of ICA method is still unclear.

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Conventional ICA-based procedures require the intervention of a trained professional to visually inspect the components extracted by ICA and identify those corresponding to artifacts [26]. This process may be complex and time consuming. In addition, disagreement among readers of the same recording is possible due to the subjective nature of the analysis.

In this study, an automated method for ECG-artifacts removal from trunk SEMG signals was proposed. The ICA method was first applied to the SEMG signals for source separation, followed by a dedicated algorithm developed for automated identification of ECG source components. Remaining components were then reconstructed to produce the "clean" EMG signal.

2. Methods

2.1. ECG-artifact separation using ICA

The raw trunk SEMG is actually a linear mixture of useful signal (EMG) and artifact (ECG). Activities from back muscle and cardiac muscle are separated processes. Their independence should be reflected in the statistical relation between their corresponding biosignal. By using this concept, the ICA algorithm decomposes the raw SEMG into distinct independent source components. Detailed discussion of the assumptions and requirements of ICA can be found in many publications regarding the mathematics of ICA [30–33].

The whole process of ICA-based ECG cancellation was illustrated by an equation listed below:

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = x \rightarrow A \xrightarrow{s} B \rightarrow y = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} = \hat{x}$$

where x and $\hat{x}$ are respectively the n bipolar raw SEMG signals and the "clean" SEMG signals after artifact removal. A is the ICA decomposition process. Once the independent components had been calculated, ECG-artifact components were identified (Fig. 1b), based on their typical morphology. Thereafter, signal reconstruction was performed with the "clean" components, s, excluding the identified artifactual components. B denotes the process of ICA "clean" signal reconstruction, and y is the processed SEMG output. In this study, the method of ICA was applied for the ECG-artifact removal process using the MATLAB package (FastICA) [34].

2.2. Detection and identification of ECG-artifact source components

2.2.1. Signal preprocessing

The ICA algorithm extracted statistically independent components from the raw SEMG signal (Fig. 1a). The number of extracted source components was equal to the number of recording electrodes. Extracted source components (Fig. 1b) were normalized after centering and whitening process of ICA [32]. They were then evaluated for similarity to ECG signals. ECG-artifact removal based on ICA either reject or preserve components extracted by the algorithm. Independent source components were classified as EMG or artifactual activities, i.e. ECG, and this process of classification was performed manually in conventional ICA-based methods.

For this purpose, an automated detection algorithm for ECG artifact was developed in this study. The proposed algorithm was performed based on the typical characteristics of ECG artifacts and their main differences from EMG signals – the spike-like property and the periodicity of corresponding R-peaks. However, in the presence of EMG background signal, there is difficulty in detecting ECG R-peaks solely by a threshold comparison approach. EMG waveforms or spikes that resemble typical ECG R-peaks could have been falsely identified.

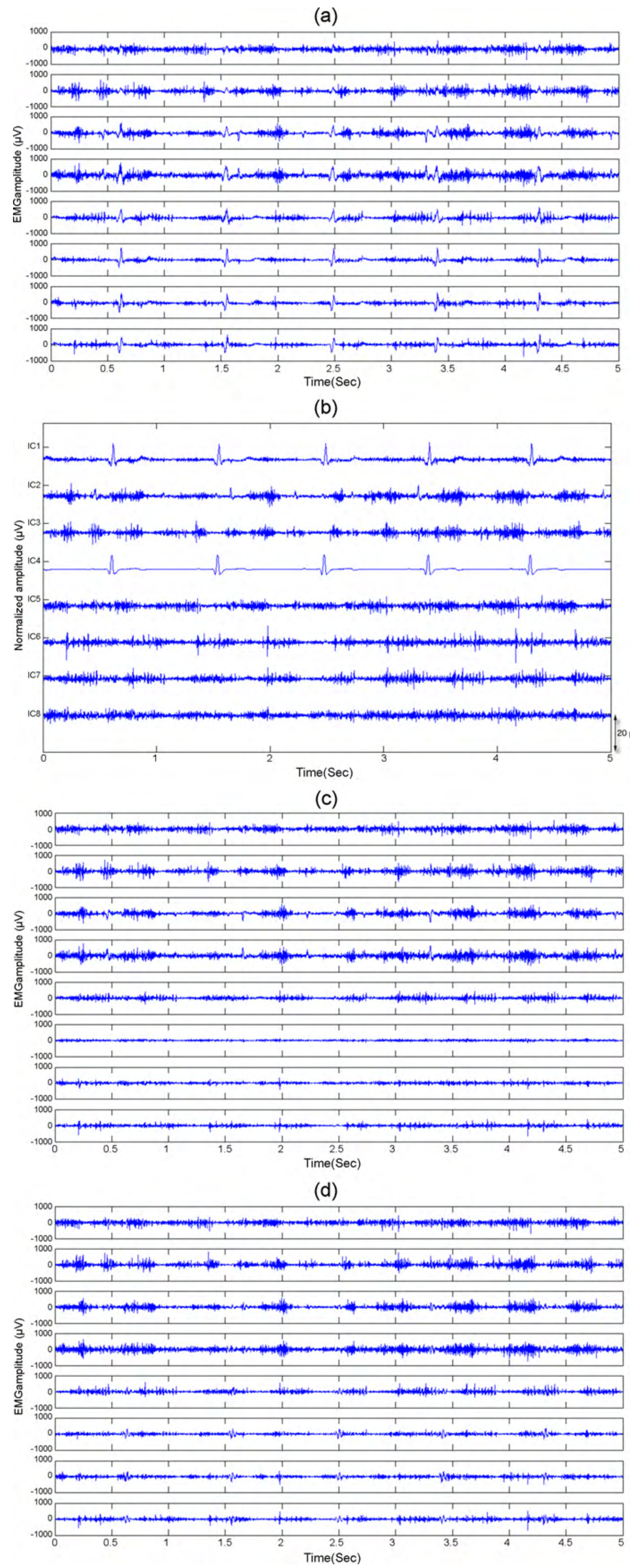

Fig. 1. The simulated SEMG data with ECG artifact. (a) Independent source components extracted by ICA. (b) SEMG data after removal of ECG artifact using ICA. (c) ECG-cleaned SEMG data processed by BW HPF 30.