ECG Artifact Removal from Surface EMG Signal Using an Automated Method Based on Wavelet-ICA

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Abstract. This study aims at proposing an efficient method for automated electrocardiography (ECG) artifact removal from surface electromyography (EMG) signals recorded from upper trunk muscles. Wavelet transform is applied to the simulated data set of corrupted surface EMG signals to create multidimensional signal. Afterward, independent component analysis (ICA) is used to separate ECG artifact components from the original EMG signal. Components that correspond to the ECG artifact are then identified by an automated detection algorithm and are subsequently removed using a conventional high pass filter. Finally, the results of the proposed method are compared with wavelet transform, ICA, adaptive filter and empirical mode decomposition-ICA methods. The automated artifact removal method proposed in this study successfully removes the ECG artifacts from EMG signals with a signal to noise ratio value of 9.38 while keeping the distortion of original EMG to a minimum.

Keywords. ECG artifact, surface EMG, wavelet transform, automated ICA.

1. Introduction

Electromyography (EMG) is a tool routinely used for a variety of applications in a very large breadth of disciplines [1]. However, this signal is inevitably contaminated by various noises and artifacts originated from different sources [2]. Electrical activity of heart muscles, electrocardiogram (ECG), is one of sources which affects the EMG signals due to the proximity of the collection sites to the heart and makes its analysis non-reliable [3]. Different methods have been proposed to remove ECG artifact from EMG signals, but removing this artifact has some difficulties due to the large overlap between the ECG interference spectrum and that of the considered surface EMG signal [4]. High pass filter (HPF) [5] is a simple and fast method that has been proposed to remove ECG artifacts from EMG signals, but it removes a significant part of the EMG information [4]. Other methods, such as adaptive filter [6], artificial neural network [7] and independent component analysis (ICA) [2] have been proposed, but they require an extra ECG reference signal that adds to the complexity of the hardware. The template

subtraction algorithm was successful in removing ECG artifacts from EMG signals, but it is sensitive to changes in the waveform of the ECG artifact [4, 8]. A new attitude in artifact removal process is to use single channel ICA [4]. Empirical mode decomposition (EMD) and wavelet transform are approaches that could enable ICA method to be used in single channel analysis [4, 9]. EMD has high computational cost and cannot be used in real time applications [10]. The combined wavelet-ICA method could successfully remove ECG artifacts [9, 11]. However, this method is user dependent. Therefore, the goal of this study is to propose an automated method based on wavelet transform and ICA to remove ECG artifacts from EMG signals and to overcome the shortcomings of each method. Moreover, a high pass filter has been employed to eliminate unwanted low frequency components. The proposed approach was compared with other common methods such as wavelet transform, ICA, adaptive filter and EMD-ICA. The performance of the proposed method was evaluated using quantitative parameters including signal to noise ratio (SNR), relative error (RE) and correlation coefficients (CC).

2. Material and Methods

2.1 Signal Recording and Simulating

Five healthy subjects were recruited among a university student population after obtaining their informed consent. Clean EMG signal (the EMG signal without ECG artifact) was collected from the biceps muscle of the right side (Figure 1a). Also, the ECG artifact was recorded from the pectoralis major muscle of the left side (Figure 1b). The signals were recorded with a sampling frequency of 2000 Hz.
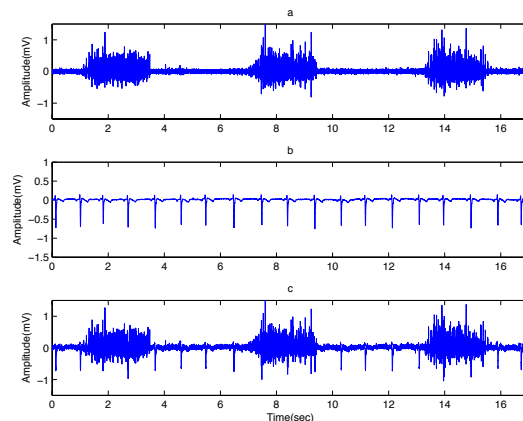

Figure 1. (a) Clean EMG, (b) ECG artifact and (c) EMG with added ECG.

To remove undesirable motion artifacts, the clean EMG signal was high-pass filtered with a cutoff frequency of 10 Hz (infinite impulse response, Butterworth order 5), and the DC value was removed from the ECG artifact. In order to obtain a quantitative evaluation of the methods, it is necessary that the corresponding clean EMG signal be available with the contaminated EMG. Therefore, the ECG artifact was multiplied by a factor and was added to the clean EMG to simulate the contaminated EMG signal. The SNR of the contaminated EMG signal was considered zero. In Figure

1c, a sample of simulated EMG with added ECG signal is presented.

2.2 Automated Wavelet-ICA Technique

The idea behind combined wavelet transform and ICA method is to decompose a single channel data into different components using wavelet transform before applying ICA technique (Figure 2).
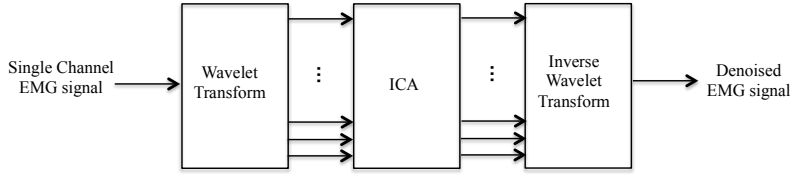

Figure 2. Block diagram of the combined wavelet-ICA method.

Wavelet transform is a time-frequency method that has been introduced to overcome the limitations in time and frequency resolutions [9]. Instead of using a sine wave, a basic function, $\varphi_{a,b}(t)$, is used which is defined in Eq. (1) [12].

$$\varphi_{a,b}(t) = \varphi_a(t-b) = |a|^{-\frac{1}{2}}\varphi(\frac{t-b}{a}) \tag{1}$$

Where "a" is the scaling parameter and "b" represents the translation parameter [12]. Wavelet decomposes a signal into different frequency components and studies each component with a resolution matched to its scale [13]. This property can be used for denoising purposes [12]. In this study, a discrete wavelet transform using the fourth-order Daubechies wavelet was applied to a single channel recording (60 seconds) to create an eight-level wavelet decomposition of the raw signal. Choosing this wavelet was due to similarity of the wavelet function to the ECG signal that helps to remove noise successfully [14]. After calculating the wavelet coefficients, independent component analysis was used to extract independent components from the multidimensional data produces by wavelet transform. Independent component analysis finds a linear representation of non-Gaussian data. When n linear mixtures $x_1(t), \dots, x_n(t)$ of m independent components $s_1(t), \dots, s_n(t)$ are observed, ICA can be used to estimate a_{ij}, the mixing matrix, based on the information of their independence, which allows us to separate the original source signals from their mixtures. A model for ICA can be written as Eq. (2) [15]. In conventional ICA-based methods, after creating the ICA components, independent components are classified manually as EMG signal or ECG artifact. In this study an automated algorithm was used to determine the ECG artifact components automatically [16]. This algorithm was performed waveform envelope to extract the main morphological features of the independent components. To obtain the waveform envelop, Hilbert transform of the independent components was obtained using Eq. (3) [16].

$$x = As \tag{2}$$

$$s_h(t) = H[s(t)] = \int_{-\infty}^{\infty} \frac{s(t-\tau)}{\pi\tau} d\tau \tag{3}$$

Where $s_h(t)$ is the Hilbert transform of $s(t)$. The waveform envelope is absolute value of the Hilbert transform. Median filter of order 50 was then applied to remove the baseline wandering in the components [16]. This procedure significantly improves R wave detection in the ICA components with ECG artifact. The next step is to find a threshold by calculating the maximum value of each component (s_{max}) and multiplying it by a factor that obtained experimentally ($Tr = 0.25{\times}s_{max}$). The component was converted into binary format using Eq. (4) [16]:

$$\begin{cases} s_t(n) = 1, & s(n) \geq Tr \\ s_t(n) = 0, & s(n) \leq Tr \end{cases} \tag{4}$$

Afterward, first derivative of $s_t(t)$ was obtained to calculate the rate of change in the binary signal [16]. Finally, three parameters were evaluated to choose the noisy component [16]; (1) number of peaks, P, was considered 40 to 100 heart beats per minute ($100 > P > 40$) (2) R wave to R wave (RR) intervals was considered 0.1 s (which is averaged RR interval with a heart rate of 40 in the wavelet domain) to 0.15 s (which is averaged RR interval with a heart rate of 100 in the wavelet domain) and (3) variance of RR intervals ($VRR < R{\times}0.2\ s$) where 0.2 s is the upper limit of RR intervals in the wavelet domain. A scaling factor R equal to 0.5 was considered in this study. Each channel of independent components was evaluated separately and the component with ECG artifact was selected automatically. After finding the noisy component in ICA-based methods, the noisy component usually is set to zero [16]. This procedure removes useful information in the reconstructed signal. Therefore, a HPF (Finite Impulse Response (FIR), Hamming window, order 100) with cutoff frequency of 20 Hz was used to remove ECG artifact from the selected component. Finally, inverse ICA and then inverse wavelet transform were applied to reconstruct the denoised EMG signal.

3. Results

In this paper, wavelet transform has been used to decompose the contaminated EMG signal into eight levels to produce multi-channels ECG signal for the ICA method. After decomposing the signal, FastICA algorithm was used to separate the desired signal from the artifact. An algorithm based on Hilbert transform was used to find the noisy ICA component automatically. Since, ECG artifact is a low frequency noise it is possible to remove it from the noisy ICA component using a HPF. Finally, inverse wavelet transform was used to obtain the denoised signal. SNR, RE, CC and elapsed time (ET) to run each algorithm using MATLAB R2014a are presented in Table 1.

Table 1. Calculating evaluation criteria (signal to noise ratio, relative error, correlation coefficients and elapsed time in second) of wavelet-ICA, wavelet transform, ICA, adaptive filter and EMD-ICA for the five simulated signals recorded from five subjects (mean ± standard deviation).

	SNR	CC	RE	ET (second)
Wavelet-ICA	10.38±1.92	0.95±0.03	0.06±0.04	2.09
Wavelet	5.36±0.81	0.86±0.02	0.15±0.03	0.37
ICA	8.05±1.08	0.92±0.03	0.09±0.04	1.64
Adaptive filter	8.09±1.29	0.92±0.02	0.12±0.04	126
EMD-ICA	9.46±1.32	0.93±0.25	0.07±0.16	6384

The elapsed time was measured by implementing the algorithms on a PC with 2.6 GHz dual-core Intel Core i5, Turbo Boost up to 3.1 GHz and 8GB 1600 MHz memory. Contaminated EMG signal, noise estimated and denoised EMG using the proposed method are presented in Figure 3.
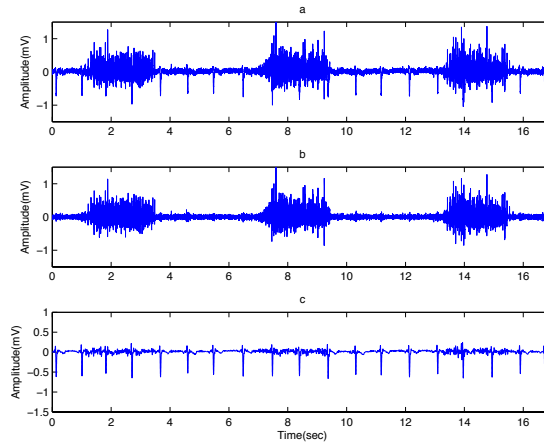

Figure 3. (a) Contaminated EMG, (b) Denoised EMG and (c) Estimated noise using the proposed method.

The proposed method was also quantitatively compared with four currently used methods. The comparison results of these methods are shown in Table 2.

Table 2. Comparing different methods for ECG artifact removal from EMG signal

	On-line operation	Not requiring multiple input	Low computation cost
Wavelet-ICA	✓	✓	✓
Wavelet	✓	✓	✓
ICA	✓	✗	✓
Adaptive filter	✓	✗	✗
EMD-ICA	✗	✓	✗

4. Discussion and Conclusion

In this study, a combined technique based on wavelet transform and ICA was proposed to remove ECG artifacts from EMG signals. The calculated values (SNR, RE, CC and ET) for this method, as listed in Table 1, show this algorithm is capable of eliminating the ECG artifact with the SNR, RE, CC and ET of 10.38, 0.06 and 0.95 and 2.09 (second) respectively. This technique is an automatic artifact removal method that does not require multi-channel signal and can operate online and automatic with a promising result for many applications. According to the comparison made in Table 2, adaptive filter is an automatic method that operates online [6, 10]. However, it requires additional sensor and also it has high computation cost (Table 1). Wavelet transform is an online method with low computation cost that does not require multiple inputs. The ICA method is an online method; however, it operates on multi-channel signal [10]. EMD-ICA is a single channel technique showed good performance compared to the

other methods investigated in this paper, but the computational cost of this method is high, which makes its real-time implementation impossible. The difference between the results of wavelet-ICA and EMD-ICA can be explained via differences in decomposing of the original signal [10]. Hence, we proposed an automatic method based on wavelet transform and ICA to address the shortcomings of the currently used methods.

Acknowledgment

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