WAVELET-BASED MOTION ARTIFACT REMOVAL FOR ELECTRODERMAL ACTIVITY

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Electrodermal Activity

- Electrodermal activity (EDA) refers to the changes in the electrical properties of the skin in response to autonomic innervation [3], which can be recorded as skin conductance (SC) [7].
- Because SC provides a fine measure of the sympathetic nervous system (SNS) activity, it is widely used in psychophysiology as an indication of physiological or psychological arousal.

Motion Artifact in EDA

- Analysis of EDA is hampered by its sensitivity to motion artifacts, even when subjects are asked to avoid gross body movements.
- As ambulatory EDA sensors are adopted in more and more studies related to affective phenomena [9, 10], sleep [17], epilepsy [16] and stress [8, 11], removing motion artifacts before further statistical treatment becomes even more essential.
- One of the most common artifacts in EDA is unusual sleep rises (see Fig. 2), stemming from pressure exerted on the electrodes [5].

Previous Methods

- There are a few methods previously taken to correct motion artifacts, such as exponential smoothing [11] and other low-pass filters [12, 15, 16].
- However, these non-adaptive methods are unable to compensate for artifacts abruptly appearing with much larger intensity than EDA, and the whole time series are filtered indiscriminately, which may distort SC signals without artifacts.

Our Method

- We have developed a wavelet-based approach to remove motion artifacts from EDA signals.
- This model fits the characteristics of SC signals well. Time series of SC can be characterized by a slowly varying tonic activity (i.e., skin conductance level; SCL) and a fast varying phasic activity (i.e., skin conductance responses; SCRs) [2]. In summary, the wavelet coefficients of an observed SC signal Y(k) can be written as

\[ E(k,j) = \phi(k,c) (Y(k) - \theta(\mu,k,j)) \]

Here we choose \( j = 1, \ldots, 8 \), which means EDA data were decomposed into 8 levels.
- Distribution of wavelet coefficients can be modeled as a mixture of two Gaussians [1, 4]. This model fits the characteristics of SC signals well.
- Therefore, motion artifacts can be removed from the wavelet coefficients using the following scheme:

Assuming \( c \) takes up a very small proportion, from the wavelet coefficients of the original signal \( a, \phi, \psi, \) and \( \epsilon \) can be estimated for each level \( j \) using an Expectation Maximization (EM) algorithm [13].
- Assume the proportion of \( \epsilon \) in \( a \) is 0 (the artifact proportion). For any given wavelet coefficient, if the probability of observing values smaller or larger than it is less than \( 0.25 \), we can conclude that the coefficient does not belong to the valid SC distribution.

Results

- EDA data containing motion artifacts was obtained from a previous study [6], in which 32 subjects completed physical, cognitive and emotional tasks while wearing Q sensors on both wrists.
- During each trial, the Q sensors recorded SC, actigraphs (acceleration) and body temperature at a sampling frequency of 8 Hz for approximately 80 minutes.
- Two expert EDA researchers reviewed in total 61 records of data to manually label portions of the SC signals as containing motion artifacts.
- To quantitatively evaluate and compare the performance of all the methods, we used artifact power attenuation (APA) and normalized mean-squared error (NMSE) [14] as criteria:

\[ \text{APA} = \frac{100 \times \sum_{j=1}^{N} \text{APA}_j}{N} \]

\[ \text{NMSE} = \frac{\sum_{j=1}^{N} (\hat{y}_j - y_j)^2}{\sum_{j=1}^{N} y_j^2} \]

Table 1: Median of NMSE and APA (in dB) for the evaluated methods.

![Figure 1. An ambulatory EDA sensor (Q sensor, Affectiva, Inc.).](image1)

![Figure 2. SC signal with motion artifacts labeled by two expert EDA researchers; Actigraph in three axes.](image2)

![Figure 3. 8 levels of wavelet coefficients with adaptive thresholding.](image3)

![Figure 4. Denoised SC signal with motion artifacts labels; Actigraph in three axes.](image4)

![Figure 5. A typical histogram of the wavelet coefficients of an SC signal with a fitted model of two mixed Gaussians superimposed. The two blue vertical lines represent the minimum and maximum values of the histogram.](image5)

![Figure 6. ~Q-Q plot of sample wavelet coefficients.](image6)

![Figure 7. Original EDA (blue lines) and denoised signals (red lines) processed by (a) wavelet thresholding (Haar wavelet [18], artifact proportion 0.01, time window length L = 400 seconds), (b) 1024-point low-pass Hamming filtering (cutoff frequency = 3 Hz) [15, 16], (c) Hamming filtering with a 1 second window [12] and (d) exponential smoothing (a = 0.8) [11].](image7)