Using Electromechanical Signals Recorded from the Body for Respiratory Phase Detection and Respiratory Time Estimation: A Comparative Study

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Abstract

Electrocardiogram derived respiratory (EDR) is a non-invasive technique to estimate respiratory signal. As an alternative, recent studies suggest using Seismocardiogram to estimate respiratory signal, so called accelerometer derived respiration (ADR). In this study we compared the performance of ADR and EDR in precise detection of respiration phases (inhale and exhale timing). We also compared time lag between breath cycles extracted by use of ADR and EDR, and ground truth (respiratory signal recorded using chest band strain gauge). For this comparative analysis, Seismocardiogram, Single lead electrocardiogram (Lead II), and respiratory signal (using a chest band strain gauge) were recorded from 19 healthy subjects. Principal component analysis (PCA) and envelope detection methods are used to compute EDR and ADR. Initial results show that ADR in z-direction (back to front) seems promising approach in addition to the EDR with accuracy of above 85% in identifying respiration phases (inhale and exhale). 87% of breath cycles extracted from ADR had acceptable time lag compared to ground truth (respiratory signal recorded using a chest band strain gauge). ADR was able to correctly classify heartbeats to inhale and exhale classes with classification accuracy of around 76%.

1. Introduction

Respiration affects the cardiovascular system significantly and this is observed in hemodynamic parameters such as stroke volume and heart rate. The morphology of signals relevant to the heart also changes with respiration. Such changes have been used to extract respiration signal from electrocardiogram (ECG) [1,2]. It is also shown that accelerometers placed on the body can be used to extract respiration signals [3–8] . In addition to ECG and accelerometer, EMFit pressure sensor has also been used to measure respiratory rate [9]. Apart from measuring the respiration rate or estimating the respiration signal morphology, what is also important is to detect the phases of respiration using the same accelerometers. It has been demonstrated that the signal morphology for seismocardiogram is different between inhale and exhale and knowing the respiration phase can assist in proper averaging of the signal [10] .

What differentiates this paper from similar works is it's emphasize on detection of the start and end timings of respiration phases and also discriminating heart beats related to inhale from those related to exhale phases rather than detecting them alone or computing respiration rates only. Thus, the idea behind this study is to compare the efficacy of ADR to EDR in detecting the respiration phases and investigate the feasibility of detecting inhale and exhale from the same accelerometer recording the seismocardiogram. In addition, investigate the possibility of estimating the timings of inhale and exhale phases in both methods. This detection and estimation can be used later to yield a differential averaging of seismocardiogram based on respiration phases of inhale and exhale.

2. Methods and Materials

2.1. Data Acquisition

Nineteen healthy male subjects with no known pulmonary or cardiovascular disease were recruited for this study. Ten minute of the respiration belt and accelerometer data was recorded at 1000 Hz sampling frequency.

The 3 axial accelerometer in [8] was mounted on the sternum using double-sided adhesive tape. The accelerometer system was positioned about one centimeter above the xiphoid process. The respiration signal was measured using a respiration belt sensor (BN-RESP-XDCR, BIOPAC Systems Inc, US). The belt sensor was tightened around the body so that it did not resist breathing, but still so tight to be capable of recording breathing.

All measurements of healthy individuals were performed at Aalto University School of Electrical Engineering, Espoo, Finland in the spirit of Helsinki declaration. The study did not contain any such intervention in the physical integrity of the test subjects, or any other features needing an ethical review as considered by the National Advisory Board on Research Ethics in Finland. A written consent was received from each subject. (Overall age, height, and weight of subjects are 24.8±3.09, 180.6±5.10 cm, 78.9±9.05 Kg).

2.2. Signal Processing

All the signal processing was performed in MATLAB. As a pre-processing step electrocardiogram signals were normalized so its mean was zero and the standard deviation was one.

Principal Component Analysis (PCA) is known as one of the popular dimensionality reduction or manifold learning methods and it has been used in analyzing seismocardiogram (SCG) [11] as well as estimating respiration signal from electrocardiogram signal in many studies using linear or non-linear kernel [12] . This method aims to illustrate as much as of the variance in the data as possible by using only a few principal components. In this study, first principal component has been used. To drive respiratory signal from electrocardiogram using the principal component algorithm, first heart beats were recognized utilizing the R peaks. In the next step, heart beats were collected in the form of m×n matrix, where m is the number of beats and n is the number of samples per beat. In the final step, principal component analysis was applied to the matrix to produce m principal component [12] .

Upper and lower envelope functions of the electrocardiogram data were calculated based on moving time window secant method, where time window size is the control parameter and is set to a value which covers dynamic range for respiration range of adult human. Two second windowing has been used for envelope detection. The Secant method is a numerical technique which can be used to find maximum slope (peak and envelope point) within each time window [13] . An envelope of the signal mostly corresponded to its respiration component.

By applying PCA or envelope detection method to ECG and SCG in z direction signals, ADR (accelerometer derived respiration) and EDR (electrocardiogram derived respiration) were obtained. Figure 1 shows respiration, ECG, SCG signals and estimated signals.

After applying envelope or PCA method, estimated signals were detrended to remove baseline wander. This process was repeated for all nineteen subjects.

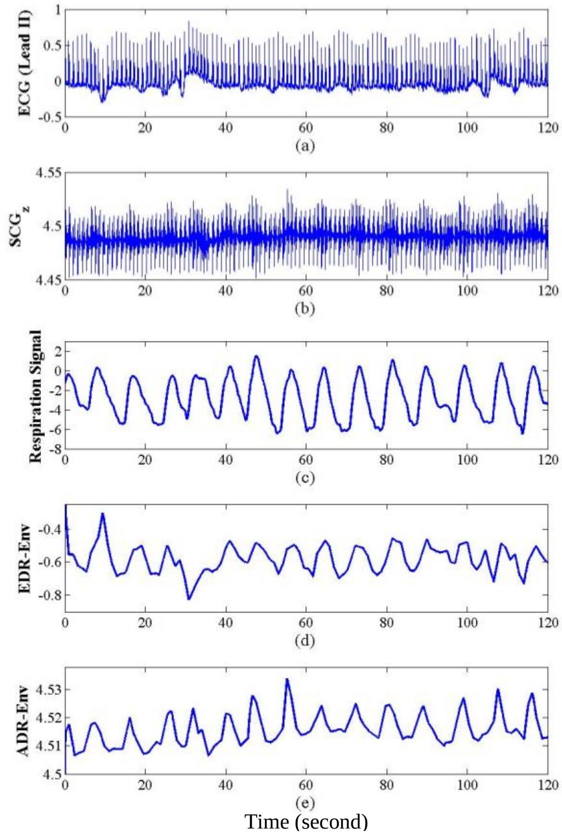

Figure 1. a) Representation of ECG (Lead II), (b) SCG in z direction, (c) respiration signal, (d) ECG signal after applying envelope detection method (EDR) and (e) ADR signal.

2.3. Manual Annotation

In order to assess the possibility of detecting the timings of respiration phases, the reference respiration signal and the estimated signals were manually annotated. In other words, the annotation were done using find peaks MATLAB function to detect beginning of inhale and exhale phases and then all the detected points were visually checked . Those that are not detected by the function, manually were added. The annotation of estimated respiratory signals (ADR and EDR) was in absence of original respiration signal (reference signal) to avoid any biased detection. Approximately, total of 2391 respiration phases were manually annotated from the reference signal.

2.4. Performance Assessment

There are two criteria to assess the performance of any technique in detecting respiration phases. The first criterion is whether the respiration phase is detected in the estimated signal, in the first place and then to find the time difference between the start and end of the detected respiratory phase compared to the same timings on the reference signal. Valleys and peaks in respiratory signal represent start of inhale and exhale phases respectively. So the second criterion is that, in the detected phases, what is the error, time difference, between the reference start points and detected points from estimated respiratory signals. In other words we are dealing with both a detection and time estimation problem and we need to report the results on both of them.

3. Results

3.1. Respiration Phases Detection

Respiratory phases (inhale and exhale) were identified in ADR and EDR signals by use of respiratory signal recorded using a chest band strain gauge. We defined a window around peaks and valleys of the reference signal, to find their corresponding on estimated signals. Depending on the width of this window, different detection accuracies were obtained. True positive is the number of peaks and valleys that were detected from estimated signal over total number of inhale and exhale phases in the reference respiration signal. Likewise, false negative is the ratio of number of start points that estimated signal did not recognized them over total number of inhale and exhale phases in the reference respiration signal.

Figure 2 shows the ADR signal vs. the reference respiration signal (respiratory signal recorded using a chest band strain gauge) for a typical subject. As Figure 2 shows the ADR signal is very similar to the original respiration belt component in terms of timing and respiration phases.

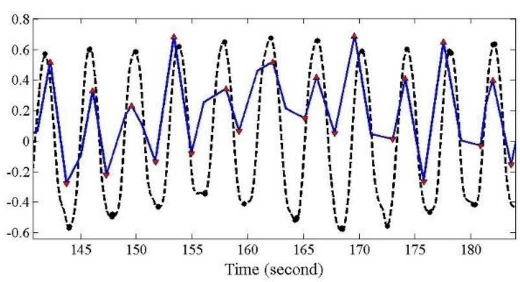

Figure 2. Detection and estimation of respiratory signal. Dashed signal is the reference respiration signal and the solid is the ADR signal.

In this study we computed sensitivity for each subject for different window sizes to find a proper window size. Window sizes of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 seconds were tested. Average sensitivity, for nineteen subjects, is shown in Figure 3.

3.2. Timing Analysis

Another factor to evaluate performance of ADR and EDR is error in timing of ADR driven breath cycles (inhale and exhale) in comparison to breath cycles extracted using respiration signal (respiratory signal recorded using a chest band strain gauge). In other words, how much of a typical breath cycle is wrongly associated to the adjacent breath cycle.

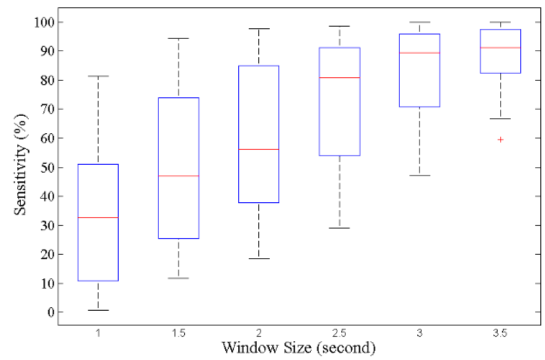

Figure 3. Effect of window size on respiratory phase detection from ADR signal in z direction.

Average heart rate, and breathing rate for all nineteen subjects respectively are 60 and 23 per minute. Therefore, there are three heart beats, on average, per respiration cycle in data for nineteen subjects.

A typical breath cycle, corresponding cardiac cycles and time difference between reference peaks and detected peaks, from ADR signal, are shown in Figure 4.

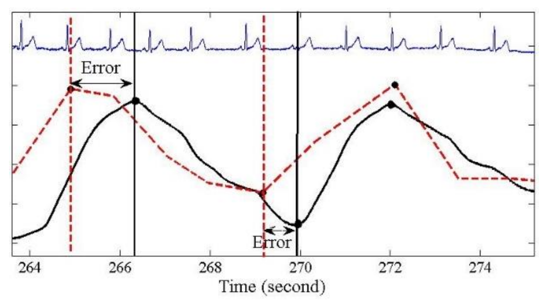

Figure 4. Cardiac cycles in each respiration phase. Solid line is the reference respiration signal and dash line is the ADR signal.

Timing analysis for the 3.0 second window size (1.5 second before and after the point) was performed to establish truly identified (reliable) portion of breath cycles in the ADR, in z-direction. The reliable percentage of respiration phases are about 87.8 % for exhale phases and 86.1% for inhale phases.

We also computed the accuracy of labeling heart cycles to inhale or exhale classes using estimated respiratory signals (ADR, EDR using envelope method). As Table 1 shows both up and down envelope methods were applied to the signals. Moreover, to compare our approach to previous studies [11], PCA method was performed for EDR, once with negative polarity and another with positive polarity. EDR signal with negative polarity is the inverted form of regular EDR signal using PCA method.

Best result between up and down envelope was chosen for each subject and then average of these results is reported in the last column of Table 1. Likewise, for EDR using PCA method, last column is the best result of positive and negative polarity.

Table 1. Average accuracy of discrimination of heart cycles to inhale and exhale phases in respiratory signal.

Estimated Signal	Up Envelope	Down Envelope	Best result
ADR_z	61.1	69.9	76.0
EDR	66.7	46.1	67.2
	Positive Polarity	Negative Polarity	Best Result
EDR_PCA	56.9	59.1	61.3

4. Conclusion and Future Work

The aim of this study was to find a proper method for detection and estimation of respiratory cycles. An envelope-based methodology was used to estimate a surrogate of respiration signal from the acceleration signal, ADR and EDR. The reference respiration signal and the derived signals were hand annotated for respiration phase detection.

Based on our observation, envelope detection method is a proper method to derive respiratory signal in addition to PCA method. Moreover; ADR can be an alternative way to detect and estimate breath cycles.

The initial results suggest that ADR in z direction, using envelope method with a window size of 3.0 seconds, has the sensitivity of about 85% for detection of breath cycles and about 87% of breath cycles extracted from ADR had acceptable time lag compared to ground truth (respiratory signal recorded using a chest band strain gauge). This means that if we remove on average 6% of initial and also 6% of final part of each detected respiration phase segment, the remaining is correctly assigned to the right respiration phase.

In addition, according to table 1, ADR in z direction using envelope method has achieved 76% accuracy to discriminate heart cycles to inhale or exhale phases. Among 19 subjects, three subjects had poor performance in this classification; put it differently, by excluding these three subject we have about 80% accuracy. In these three subject we saw irregular time interval patterns and dynamic range was low which could be due to the location of sensors or anatomy of subjects, since EDR signal using envelope method had better performance for these three subjects. Thus, fusion of ADR and EDR signals can be a solution for low amplitude subjects. We also can conclude that if the dynamic range of estimated signal is lower than a specific value (threshold), the performance will be unsatisfactory.

The next step for this study is to fuse ADR and EDR signals to improve quality metric to detect heart cycles related to inhale or exhale phases. In addition, automate the algorithm for detection of the peaks and to test the algorithm on more subjects and different respiration rates.

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