Beat to Beat Estimation of cosRT Angle and cosRT RR Hysteresis from Exercise ECG Measurement

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Abstract: Method for estimating beat-by-beat cosRT angle from the 12-lead exercise electrocardiogram (ECG) measurement is presented. Method uses principal component regression to generate ECG waveform model, and uses this model to denoise QRS complexes and T-waves. In addition two different methods for synthetizing vector ECG from the conventional 12-lead measurement are compared. First method synthetize vector ECG by using inverse of the Dowers matrix and second method produces vector ECG by using singular value decomposition. Results indicate that vector ECG synthesized using Dowers matrix gives more comparable results for healthy subjects. Beat-by-beat cosRT estimation revealed that due to respiration angle values can vary as much as 70 degrees, because of changes to electrode positions and volume conduction model of the torso. Thereby presented method for beat-by-beat estimation of the cosRT angle can improve reliability of this parameter.

1 INTRODUCTION

Exercise electrocardiogram (ECG) measurement has been used decades as a clinical tool for detecting several cardiac diseases such as ischemic heart disease. Recent studies have shown that exercise measurement can be also used for predicting sudden cardiac death for general population and after myocardial infarction (Zabel et al., 2000; Kardys et al., 2003; Kenttä et al., 2010; Kenttä et al., 2011). In addition cosRT angle and its relation to heart rate during exercise has been shown to have prognostic value (Kenttä et al., 2012). cosRT angle has been shown to relate to heart rate level, however this relation differs during exercise and recovery periods i.e. cosRT angle return towards the normal values slower than the heart rate. This phenomenon is called as cosRT/RR hysteresis. It is shown that cosRT RR relation is disrupted in patients with cardiac events (Kenttä et al., 2012).

The cosRT angle can be estimated from vector ECG (VECG) which is measured using Franks lead configuration. Thereby traditionally measured 12 lead ECG must be transformed to correspond ECGx, ECGy and ECGz leads of VECG measurement. There are two commonly used methods to synthetize VECG leads from the 12 lead measurements. First method is so called Dowers method were inverse of the Dowers transformation matrix is used to produce x, y and z VECG leads (Dower et al., 1980; Edenbrandt and Pahlm, 1988). Second possibility is to use singular value decomposition (SVD) to produce three orthogonal ECG components from the 12 lead measurements. In this paper we compare these two techniques to synthetize VECG components using three exercise ECG measurements and the beat-by-beat cosRT angles estimated from ECGx, ECGy and ECGz components produced by both methods are compared.

The cosRT angle is traditionally estimated using averaged beat epochs, but in this paper a method for estimating cosRT angle beat-by-beat is presented. Method uses principal component regression (PCR) to generate ECG waveform model, and uses this model to denoise QRS complex and T-wave epochs. It is assumed that by using beat-by-beat estimates of cosRT angle, its relation to heart rate can be better characterized and abnormalities could be found more reliably.

2 MATERIALS AND METHODS

2.1 Constructing x, y and z Leads

Before the VECG synthetization, baseline wander

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caused by chest movements were removed from the ECG by applying a median filter in a 1 s long window and by subtracting the acquired baseline from the original ECG. Secondly, EMG and power line noise were reduced using a sixth order Butterworth low pass filter with a cut-off frequency at 48 Hz.

In this study, two methods for synthesizing ECGx, ECGy and ECGz leads from the conventional 12-lead measurement were used. First method was Dowers method where inverse of the Dowers transformation matrix is used to synthetize VECG leads (Dower et al., 1980). Dowers matrix is based on the Franks torso model and was created for achieving 12-lead ECG diagnostics from the Frank VECG recordings (Dower et al., 1980; Edenbrandt and Pahlm, 1988). Synthetized leads produced by Dowers method are designated here as ECGx_{dow},ECGy_{dow} and ECGz_{dow}.

Second option for synthetizing three independent leads from the conventional 12-lead ECG is singular value decomposition (Acar and Koymen, 1999). The idea in using the SVD algorithm is to produce three orthogonal ECG components, rather than approximation of the Frank lead system. In SVD, ECG data matrix Z, the rows of which contain the 8 independent leads of the 12-lead ECG is decomposed into three individual matrixes:

$$Z = U\Sigma V \text{ where, } \mathrm{UU^T} = \mathrm{VV^T} = \mathrm{I} \tag{1}$$

U and V matrixes are orthonormal and they are generally called as left and right singular matrixes. After the SVD decomposition, first three components (eigenvectors) of the left singular matrix U are used as VECG components. Properties of SVD method ensures that first component contains most of the energy of ECG and second component most of the remaining energy under the restriction of orthogonality to the first component. First three orthogonal components are used for cosRT estimation and are designated here as ECGx_{svd}, ECGy_{svd} and ECGz_{svd}.

3 PCR MODELING OF ECG

After the construction of the ECGx, ECGy and ECGz leads, the R-waves were detected using an adaptive QRS detector (Tarvainen et al., 2014). Secondly PCR modeling was used to improve signal to noise ratio. Idea of the PCR modeling is to collect QRS complexes and T-wave epochs to individual data matrixes and create data driven model for QRS complex and T-wave epochs. Here basic principles of this method are presented, for more detailed description see (Lipponen et al., 2013; Lipponen et al., 2010).

First QRS complexes and T-waves must be extracted from all VECG leads (ECGx, ECGy and ECGz). Because QRS-complex duration is rather constant regardless of the heart rate, QRS-complexes can be extracted using constant window. T-wave duration on the other hand is highly related to heart rate and thus dynamic window is used for T-wave extraction.

$$\begin{aligned} z_{\text{QRS}} &= [-0.1, 0.1]\,s \\ z_{\text{T}} &= \left[0.1, \frac{2}{3}RR\right] s \end{aligned} \tag{2}$$

were R-wave fiducial points are used as a zero point (t=0) and RR is the mean RR interval length. Next, modeling of the (i:th) wave epoch (z_i) is presented, similar procedure is used for all QRS complex and T-wave epochs in the ECGx, ECGy and ECGz channels.

1 Collect 50 previous and 50 following wave epochs to measurement matrix Z
$$Z = [z_{i-50}, z_{i-49}, \ldots z_{i+49}, z_{i+50}]$$
2 Construct four most significant PCR basis vectors, which are eigenvectors (v_k) of the data correlation matrix (R)
$$R = \tfrac{1}{100} ZZ^T$$
$$Rv_k = \lambda v_k$$
3 Use PCR basis vectors for modeling epoch z_i
$$z_i = H\theta + e$$
where $H = [v_1, v_2, v_3, v_4]$.
4 LS solution for the model parameters
$$\hat{\theta}^{PC} = H^T z$$
5 Modeled wave epoch is estimated as
$$z_i^{PC} = H\hat{\theta}^{PC}$$

Model basis vector must be estimated dynamically because during exercise increase of the heart rate causes changes to position and shape of the T-wave. By using 50 previous and 50 following wave epochs heart rate changes does not disrupt the model basis vectors and sufficient prior information is achieved. Four most significant PCR basis vector are capable to model individual waveform and its normal variation and random noise is left out for less significant basis vectors.

4 cosRT ESTIMATION

cosRT angle estimation was performed in beat-by-beat manner directly from the PCR-modelled QRS and T-wave epochs. By using PCR modeling SNR of the ECG can be increased such that beat-by-beat detection of the cosRT angle is possible. cosRT angle is defined as the cosine of the dominant vectors

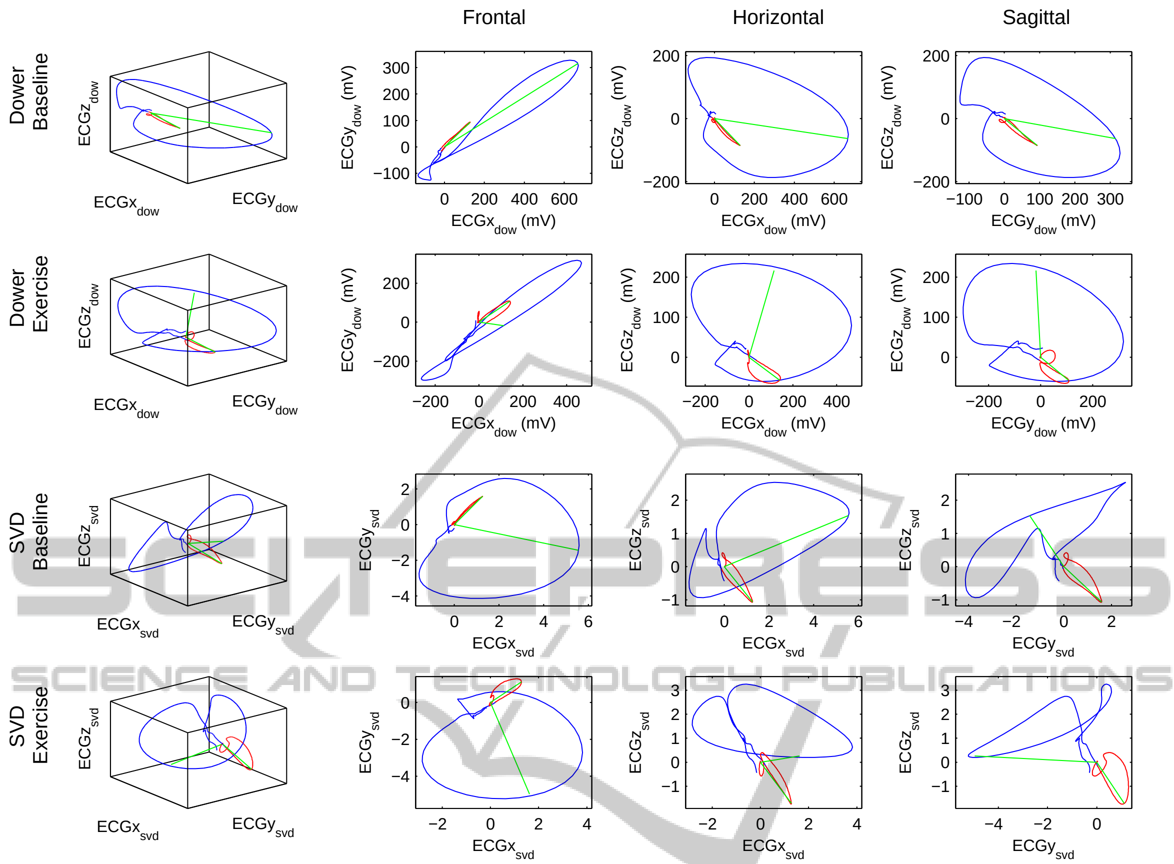

Figure 1: Examples of vector loops constructed by using inverse of the Dowers matrix and SVD. First row and second row vector loops are estimated using inverse of the Dowers matrix. First row presents VECG loops during the baseline period and second during the exercise period. Similarly vector loops produced by SVD are presented in third and fourth rows.

(80% of the maximum value) of the QRS vector loop and the main vector of the T-wave loop. Its value is limited in the range [-1,1] where -1 reflects the situation where vector loops are pointing at the opposite directions and 1 reflects the situation where the loops are pointing at the same direction. cosRT angles estimated from the VECG synthetized by using Dower's method are designated as $\cos RT_{dow}$ and similarly cosRT angles estimated from the components produced by SVD are designated as $\cos RT_{svd}$.

4.1 Measurements

Presented methods were tested using three different incremental exercise tests on cycloergometer. Three healthy male subjects participated to the measurements. Measurements were performed by using a Cardiovit CS-200 ergospirometer system (Schiller AG). ECG electrodes were placed according to the conventional 12-lead system with the MasonLikar modification. Sample rate of the ECG was 500Hz. In the measurement, subject first lay supine for 3 min, and then sat up on the bicycle for the next 3 min. After this bicycle load was initially set to 40W and the load was increased with 40W every 3 min. Subject continued exercise until exhaustion. After the subject indicated that he could not go on anymore, the exercise test was stopped and a 10 min recovery period was measured.

5 RESULTS

Figure 1 presents examples of the vector loops constructed by using inverse of the Dower's matrix and SVD before and during the exercise. From the vector loops constructed by Dowers inverse matrix, it can be seen that during exercise QRS dominant vector shifts towards the S-wave part of the QRS loop. This sifting is clearly visible at least in horizontal and sagittal projections. T-wave loop direction remains rather constant during the whole measurement. From the SVD synthetized vector loops similar sifting is clearly visible at the projection of second and third component

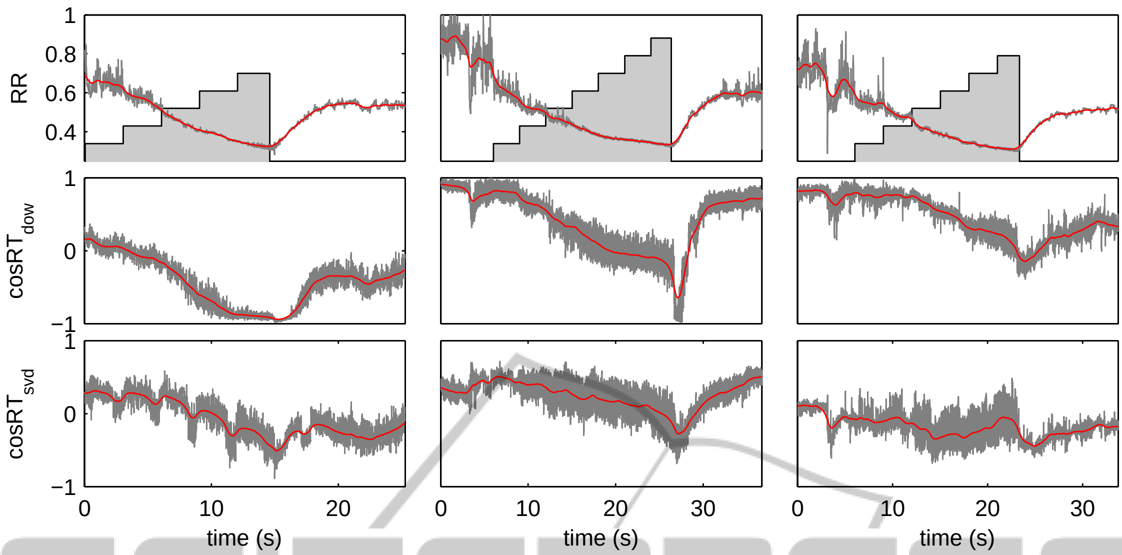

Figure 2: Estimated time series from all three subjects. First row presents RR interval time series in dark gray and used load in light gray fill. Second and third row presents estimated beat-to-beat time series of the cosRT angles. In second row, angle is calculated from the vector loops constructed by Dowers inverse matrix and in third row cosRT is estimated from the SVD synthetized vector loops. Trend of each time series is peresened as red line.

(ECGy and ECGz), however also loop morphology changes significantly caused by the changes in the third (least significant) SVD component.

In figure 2 beat-to-beat time series of RR-interval and cosRT angles are presented for all three subjects. $cosRT_{dow}$ seems to behave rather similarly for all subject, it decreases along the heart rate and after the exercise it slowly returns towards baseline. $cosRT_{svd}$ behavior is also rather similar as $cosRT_{dow}$ although in third subject there can be seen small increase at the end of the exercise period.

Figure 3 presents cosRT changes as a function of the RR-interval during exercise and recovery periods. cosRT values were divided into a bins according to coincident RR-interval, used bins were [0.35 0.4 ... 0.85] s and mean ± standard deviation of each bin is presented in the figure 3, during the exercise using red line and using blue line for the values estimated during the recovery period. $cosRT_{dow}$/RR hysteresis is clearly visible in all three subjects. $cosRT_{dow}$ returns towards the normal values slower than the heart rate and mean values of the $cosRT_{dow}$ bins forms nice hysteresis curve. $cosRT_{svd}$ on the other hand does not form as clear hysteresis curve as $cosRT_{dow}$, at least in third subject $cosRT_{svd}$ values during the recovery period are similar as during the exercise.

6 DISCUSSION

Beat-to-beat estimation method of the cosRT angle from the standard 12-lead ECG measurement has been presented. In addition cosRT angles defined from vector loops synthetized using two different methods were compared. Results show that cosRT changes during the exercise are more comparable between the subjects if Dowers inverse matrix is used for VECG synthetization.

Earlier studies have shown that in SVD synthetized VECG most of the signal energy is contained in the first two decomposed channels (Acar and Koymen, 1999). In third channel ECG power is low and thus small changes in the potentials of the heart can induce large morphological changes into this third channel. This could lead to unexpected variation in the $cosRT_{svd}$ angles. However it could be meaningful to study if all relevant information of the $cosRT_{svd}$ can be captured using only the two most significant synthetized ECG leads.

Beat-to-beat variation of the cosRT angle is significant, as can be seen in figure 2. Variation during intense exercise can be as large as 70 degrees and this variation is most likely caused by respiration. In cosRT time series respiration rhythm is clearly visible in all parts of the measurement. Respiration causes changes into the electrode positioning with respect to the heart (due to chest movements), but also it causes continuous changes to the characteristics of the

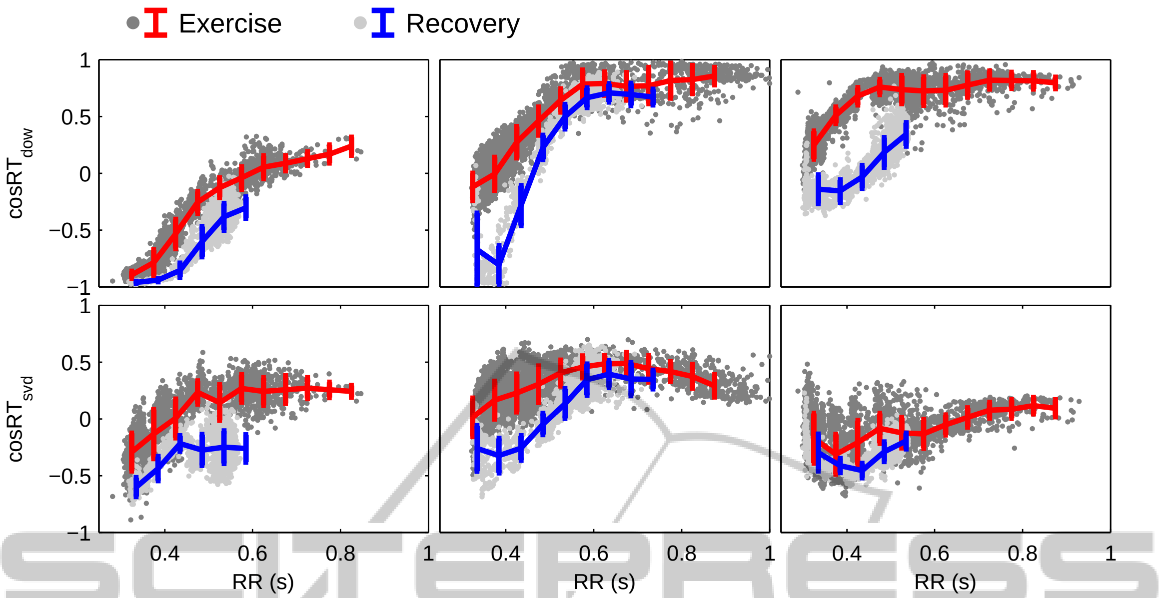

Figure 3: cosRT changes as a function of the RR-intercal during exercise and recovery periods are presented for all three subjects. First row presents cosRT$_{dow}$ angles and second row cosRT$_{svd}$ angles. Estimated angle values during exercise are marked as dark gray and during recovery period as light gray. cosRT values were divided into bins depending on current RR-interval, mean±SD during exercise are shown in red and during recovery in blue lines.

torso's volume conduction model. Both of these issues cause changes into the ECG components and to the estimated cosRT angles. Beat-by-beat estimation methods are important, because the effects of respiration can be better observed and when necessary can be taken into account in the analysis, and thereby, the reliability of the VECG parameters such as the cosRT angle could be improved.

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