Feasibility of 24-hour Monitoring and Circadian Analysis of the Cardiac Electro-Mechanical Activity Using Wearable Inertial Sensors

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Abstract

This study investigates the application of wearable technology for continuous monitoring of cardiac electro-mechanical activity in real-world scenarios, utilizing ECG and seismocardiographic (SCG) signals acquired for 24 hours through inertial sensors. In 22 healthy volunteers, a single-channel ECG (fs = 1024 Hz) and SCG (triaxial accelerometer and gyroscope, fs = 64 Hz) signals were simultaneously recorded using a wearable device. Based on the ECG, the quality of the SCG for each cardiac beat was analysed and heartbeats were labelled to exclude artefacts, and to allow detection of cardiac mechanical events, such as isovolumetric contraction, aortic valve opening and closure, from which left ventricular ejection time (LVET) and other contractility-related SCG parameters were derived. Lastly, the circadianity of the computed parameters was evaluated. High feasibility of SCG beats detection was reached during the night-time (82[69.9;90.1]%) compared to the day (49.9 [40;52]%). The presence of circadian patterns in both morphological and temporal SCG-derived parameters was for the first time evaluated and confirmed, thus enhancing the capabilities of a commercially available device typically used for postural analysis. Day-night differences could serve as reference ranges for comparison with future patient data.

1. Introduction

Cardiovascular (CV) diseases represent the principal cause of death across the globe. To cope with the increasing progression of CV diseases, new modalities for treating and monitoring patients at home are needed [1]. Technological development and device miniaturisation open the possibility for wearable devices to be used for physiological data collection. Among the emerging non-invasive techniques, seismocardiography (SCG) is one of the most promising. Using small, portable, user-friendly and unobtrusive devices, it captures the precordial micro-vibrations generated by cardiac mechanical events such as myocardial contraction and valves opening and closing [2]. Previous research has demonstrated the correlation between SCG waveform features and parameters such as stroke volume and cardiac contractility [3], making it a valuable tool for monitoring cardiac activity. However, most studies involving SCG have been conducted under controlled laboratory conditions and with limited data duration [4].

In this study, we aimed to assess the feasibility of 24-hour ECG/SCG monitoring and analysis in a real-world setting, by using a commercially available wearable device primarily designed for postural analysis using inertial sensors. To this aim, we propose a novel method based on labelling for the quality of each beat on the SCG and then extracting respective parameters relevant to cardiac electro-mechanical activity, along with the evaluation of their circadianity.

2. Material and Methods

2.1. Study population and design

Twenty-two healthy volunteers (15 females and 7 males, age: median[25^{th} percentile;75^{th} percentile] 29.5[25;54.8] years, BMI: 23.3[21.1;24.5] Kg/m^2) were recruited for a 24-hour combined acquisition of SCG and ECG signals, where the subjects were free to engage in their routine daily activities in an uncontrolled environment. The EcgMove4 sensor (Movisens Gmbh, Germany) was used, positioned between the 5^{th} and 6^{th} ribs: it records simultaneously a single channel ECG signal (fs = 1024 Hz) and the linear accelerations and angular rates along 3-axes (fs = 64 Hz). The experimental protocol, in agreement with the ethical principles of the Helsinki Declaration, was approved by the Ethical Committee of Politecnico di Milano. Each participant provided written informed consent to participate in the related activities, and, in addition, to report main activities and relevant timing. Participants were also requested to fill out a diary to report main activities and relevant timing.

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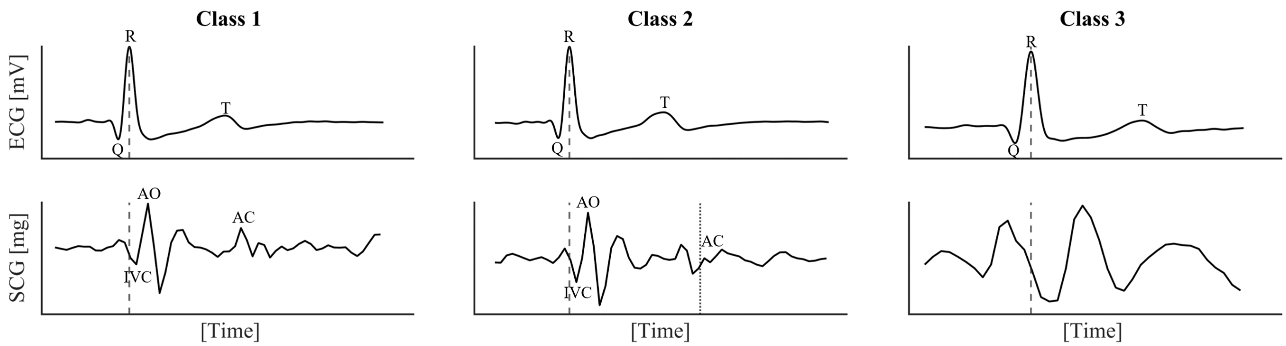

Figure 1: Heartbeats categorized into classes 1, 2, and 3, with the R peak position indicated by the dotted line. In class 2, the smaller dotted line denotes the maximum allowable position for AC, considering the physiological distance between Q and AC

2.2. ECG and SCG signal processing and parameters computation

ECG and SCG signals were pre-processed to remove noise and breathing-related motion artefacts using a 4° order, zero-phase, band-pass Butterworth filters (ECG: 0.5-30 Hz; SCG: 5-25 Hz) [5]. ECG and SCG signals were divided into 30 sec segments. The Pan Tompkin algorithm was applied to each ECG segment to extract the R peaks [6].

As concerns the SCG signal, in accordance with previous studies [5], the dorso-ventral component of the linear acceleration was selected for the analysis, as it has been proven to contain more information relevant to the heartbeat occurrence.

Afterwards, an innovative ECG-dependent approach, combining signal morphology, cardiac properties and physiological information, was implemented on each 30-second segment in order to classify SCG heartbeats and identify the analysable beats over the 24 hours.

The initial phase involved detecting systolic complexes on the SCG using an ECG-free algorithm based on the template matching technique as described in [5]. The identified systolic complexes were then compared with the previously identified ECG beats, defined as ([R_i – 200 ms; R_{i+1} - 200 ms]), with i being the i-th beat. Subsequently, the fiducial points searching algorithm was applied to the SCG signal.

The fiducial points relevant to the aortic valve opening (AO) and the isovolumetric contraction (IVC) were searched using information related to the systolic phase of the ECG (Figure 1) [7]. For each heartbeat, the aortic valve opening (AO) was defined as the first occurring maxima in the SCG after the R peak, while the isovolumetric contraction (IVC) was identified as the minimum peak between AO and the point corresponding to the closure of mitral valve (empirically found within 40 ms from the R peak).

The morphology of the ECG signal in each subject was visually inspected to assess the visibility of the T-wave. When visible, the T-wave's end location was determined using a method based on computing successive trapezium areas, with fixed and mobile vertexes [8]. If the T-end was identified, aortic valve closure (AC) was defined as the first peak after the end of the T-wave on the SCG.

Additionally, the Q-peak and the onset of the Q-wave on the isoelectric segment were found for each ECG segment.

For those beats in which the distance between Q and T-wave end (i.e. QT) and between Q and AC fell outside physiological values [9,10], the AC point was considered not reliable, and then excluded.

Each window was automatically labelled based on the detected fiducial points (i.e., IVC, AO, AC) in the SCG signal. This labelling aimed to characterize single SCG beats as schematized in Figure 1, and specifically: Class 1, when both systolic and diastolic phases were detected; Class 2, if only the systolic phase was detected; Class 3 if the beat was not analysable.

Lastly, from each beat whose label allowed their computation, the following temporal and morphological parameters were calculated [11]: the beat-to-beat duration from the ECG (RR) and the SCG (AO-AO) signals; the time delays between AO and AC (left ventricular ejection time, LVET); the slope (Slope) computed as the difference in amplitude between the AO and IVC, divided by their difference in time; and the difference in amplitude (ΔA) between the IVC and AO.

2.3. Circadianity and statistical analysis

This analysis was carried out separately for day-time and night-time along the 24-hour acquisition. The start and end of the night period were determined based on participants' daily diary entries (onset of sleep period: [min; max][9 PM; 3 AM]; onset of the day period [5:40 AM; 10:30 AM]).

The circadianity of the computed parameters was assessed, separately for each subject, using the Cosinor analysis [12], resulting in a value of Mesor, which corresponds to the midline of the oscillation, the amplitude of circadian oscillations (OA), computed as the distance between the peak of the Cosinor curve and the Mesor, and

	Subjects with detectable T-wave		Subjects with not-detectable T-wave	
	Day [%]	**Night [%]**	**Day [%]**	**Night [%]**
Class 1	15.1 [5;20.7]	19.5 [9.4;43.2]	0 [0;0]	0 [0;0]
Class 2	30 [27.1;36.5]	50.6 [36.2;67.9]	25.4 [23.1;32.8]	73.1 [54.4;77.7]
Total Analyzed	49.9 [40.5;52.3]	82 [69.9;90.1]	25.4 [23.1;32.8]	73.1 [54.4;77.7]

Table 1: Median, 25th, and 75th percentiles of analysed heartbeats, separately for day and night. Analysed heartbeats include those with both systole and diastole parameters (Class 1), as well as those with only systole parameters (Class 2)

the acrophase (φ), indicating the time corresponding to the positive peak of the curve. Lastly, the presence of the circadian rhythm was assessed using the Zero-Amplitude test ($p<0.05$).

All data points were translated to align with the chosen starting time of 8 AM. Day-night differences for each parameter were further verified using the Wilcoxon Signed Rank test ($p<0.05$).

3. Results

3.1. Feasibility analysis

Following ECG visual inspection, the T-wave was identifiable in 15/22 (68%) participants. Feasibility analysis was conducted based on the beat-to-beat labelling. Table 1 highlights the proportion of the SCG signal that resulted suitable for parameters extraction, from which it is visible how a greater portion of the signal was discarded during daytime compared to nighttime, as well as the larger number of beats in which only systolic points (i.e., AO and IVC) were detectable.

3.2. Circadian analysis

Based on the previously described visual and statistical analysis of data distribution, Table 2 reports the results of day and night comparisons. All parameters showed a significant difference: RR and AO-AO were similarly behaving as expected, while a lengthening of LVET, together with a decrease in ΔA and slope of the IVC-AO tract was noticed during the night.

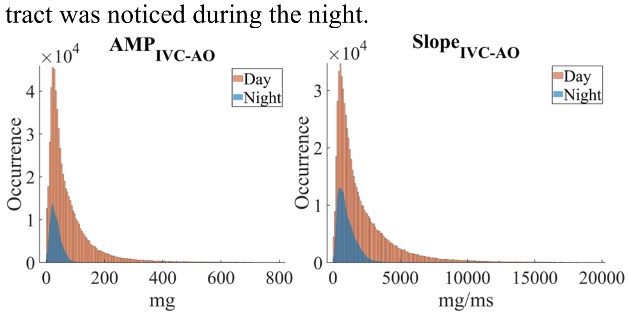

Figure 2: Cumulative distribution of ΔA and Slope. The x-axis represents the amplitude [mg] and slope value [mg/ms] respectively. The y-axis represents the frequency of occurrence of those values, separately for the day (in orange) and the night (in blue).

Table 2 shows the results of the Cosinor analysis: RR, AO-AO, and LVET exhibited their φ between 4 AM and 4:20 AM. In contrast, ΔA, and Slope showed their φ around 4 PM. All parameters were found to be statistically significant (Zero-Amplitude test) and exhibited a circadian rhythm in at least 90% of participants.

The oscillatory trend of both morphological and temporal parameters showed a small variation. However, OA/Mesor exhibited notably higher values in morphological parameters than in temporal parameters, indicating an almost twofold increase in their oscillatory trend.

4. Discussion

We tested the feasibility of analysing 24-hour ECG/SCG recordings for extracting cardiac electro-mechanical parameters. The proposed method, which combines ECG morphology and physiological knowledge, allowed for the identification of analysable heartbeats and the extraction of key fiducial points from SCG signals. These points were then used to derive parameters relevant to the electro-mechanical activity. In this way, non-analysable beats were excluded, thus resulting in a more robust characterization of cardiac phases and parameters throughout day and night periods.

Despite the low sampling frequency (64 Hz) of the SCG, the proposed approach seemed reliable enough to provide a day-night difference for all the considered parameters, highlighting similar values between RR and AO-AO, as well as circadianity in LVET, ΔA and Slope.

As expected, during night-time the % of feasibility was higher than day-time, due to reduced movement artefacts in the SCG signal. For AO-AO and LVET, φ occurred between 3:50 AM and 4:30 AM, a circadian behaviour in accordance with the RR [13], as well as with myocardial contractility and stroke volume [11,14]. LVET, inversely related to heart rate and measuring left ventricular function and myocardial efficiency [15], showed a significant day-night difference. Morphological parameters such as ΔA and Slope also displayed significant differences between day and night, presenting the φ around 4 PM [16].

5. Conclusion

This research shows for the first time the feasibility of 24-hour combined ECG/SCG acquisitions and analysis in

Parameter	Day	Night	OA/Mesor [u.a]	Φ [h: mm]	Circadian Presence *
RR [ms] (N=22)	744.1 [684.6;809.6]	937.5 * [859.4;1035.2]	0.15 [0.08;0.2]	4:06 [2:57;5:46] AM	22/22 100%
AO-AO [ms] (N=22)	767.1 [713.9;829.1]	945.3 * [865.2;1044]	0.15 [0.07;0.19]	4:20 [3:13;6:03] AM	22/22 100 %
LVET [ms] (N=15)	250 [230;250]	280 * [272.5;300]	0.12 [0.09;0.16]	3:52 [2:59;5:16] AM	15/15 100%
ΔA [mg] (N=22)	43.4 [36.4;63.6]	27.7 * [20.6;41]	0.38 [0.24;0.5]	3:53 [2:28;7:18] PM	20/22 90.91%
Slope [mg/ms] (N=22)	1.1 [0.9;1.6]	0.8 * [0.6;1.3]	0.36 [0.19;0.45]	4:04 [1:45;7:02] PM	20/22 90.91%

Table 2: The second and third columns display the comparison of parameters between day and night (median [25th; 75th percentiles]). *: p<0.05 day vs night (Wilcoxon Signed Rank). The last three columns show the results of the Cosinor analysis, with the final one indicating the significance [%] across all participants from the Zero-Amplitude test.

a real-world scenario, by extending the potential of a commercially available wearable device in which inertial measures are conventionally used only for postural analysis to continuous cardiac monitoring.

This study also showed circadian rhythms in cardiac mechanical parameters and established normality ranges from 22 healthy volunteers, for day- and night-time, that could be used as a reference for comparison in future studies involving pathological patients. Furthermore, this study constitutes the basis for future work for the development of machine learning algorithms for the automated classification of beats on the 24-hour SCG signal.

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