Assessing Cardiac Electro-Mechanical Deconditioning During Bed Rest Using Smartphone's Inertial Sensors

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Abstract

This study evaluated the potential of using smartphone-acquired seismocardiographic (SCG) signals for monitoring cardiac deconditioning after prolonged bed rest (BR). Ten healthy volunteers were enrolled in a 10-day BR. By positioning a smartphone on subject's chest, 1-minute SCG was acquired before the BR (PRE), on the 10th day of BR (BR10), and one day after reambulation (R+1). Signals were pre-processed and automatic beat identification was performed. Heart rate and variability indices (SD_{AO-AO}, RMSSD, SD_{AO-AO}/RMSSD) were calculated. Isovolumetric contraction (IVC), aortic valve opening (AO) and closure (AC) points were identified on the SCG, from which amplitude difference (AMP_{AO-IVC}) and slope were derived. Finally, linear (iK_{lin}) and rotational (iK_{rot}) kinetic energies were calculated. At BR10 sympathetic modulation at awakening increased. Also, SCG morphology was affected, with increased AMP_{AO-IVC} and IVC-AO slope. Further, at BR10 changes in morphology recovered, while iK_{lin}/iK_{rot} ratio increased. These findings support smartphones' potential as portable and non-invasive cardiac health monitoring devices for cardiac deconditioning.

1. Introduction

Extensively used in the past as a therapeutic modality, bed rest (BR) is nowadays generally linked to ageing, critical disorders [1] and extended hospitalisation periods, such as due to COVID-19. In addition, body (mal-) adaptation to prolonged BR presents several analogies with the effects of spaceflight on human body. Specifically, it reproduces the reduced physical activity, the lack of bearing weight and the upward shift of body fluids. BR is therefore currently used by space agencies to study the physiological alterations caused by prolonged permanence in microgravity [2].

Prolonged permanence in supine position additionally causes a chronic shift of body fluids towards the head and the thorax, leading to hemodynamic changes, increased thromboembolic risk and insulin resistance [3]. As an adaptation to the upward shift of fluids, the stroke volume reduces, causing changes in blood pressure [4]. Heart rhythm variability is affected as well [5], with additional repercussions on blood pressure regulation. The induced cardiovascular deconditioning acutely manifests at the reinstatement of the normal orthostatic posture, with decreased exercise capacity and hazardous episodes of orthostatic intolerance [6].

Thanks to the embedded sensors, smartphones could serve as powerful, non-invasive and easy-to-use portable tools for monitoring cardiac health [7]. When positioned in contact with the thorax, the integrated micro-electro-mechanical systems can sense the precordial accelerations or vibrations of the chest caused at each cardiac beat by myocardial contraction, valves opening and closing, and the blood ejection into the aorta [8]. The resulting signal is known as seismocardiogram (SCG). We hypothesized that the SCG signal, acquired by a common smartphone, could be used to detect changes induced by cardiac deconditioning generated by 10 days of BR. Accordingly, the aim of this study was to assess the feasibility to monitor cardiac deconditioning induced by horizontal BR through different SCG signal processing methodologies to characterise both cardiac electrical and mechanical activity.

2. Materials and methods

2.1. Study population and design

Ten healthy male volunteers (median[25th percentile; 25th percentile], 21[20.25;24] years old) were enrolled at the Hospital of Izola (Slovenia) to participate into a 10-day strict horizontal BR campaign, promoted by the Italian Space Agency and ethically approved by the National medical ethics committee of the Republic of Slovenia (No. 01210-304/2019/9), as well as registered at clinical trials repository (Clinical Trial.gov: NCT04081467). Each subject provided written informed consent to participate in BR and in the relevant experiments. The study included 2 days of baseline data collection, 10 days of strict BR, and 2 days of post-bed rest reambulation and recovery. The height and mass of each subject was measured before (PRE) and after the BR (BR10).

2.2. SCG signal acquisition

The SCG signals were acquired using the "SensorLog" app, version v.3.7.1, which was installed on a smartphone (iPhone Xs). Signals from the tri-axial accelerometer and the tri-axial gyroscope embedded in the smartphone were recorded by positioning the smartphone on the subject's sternum (fs = 100 Hz [9]) with the subject in supine position. Particularly, the x axis represents the left-right component, the y axis denotes the head-to-foot component and the z axis stands for the antero-posterior component. The validation and quality of the smartphone-acquired SCG signals using the "SensorLog" smartphone application was demonstrated in our previous work [9].

The protocol included three acquisitions of one-minute duration each, scheduled one day before the BR (PRE), at BR10 before bed rest discontinuation, and one day after reambulation (R+1). All acquisitions were performed between 7:15AM and 7:30AM.

2.3. SCG signal pre-processing

Each of the six SCG channels (x, y, z of the accelerometer and x, y, z of the gyroscope) was band-pass filtered using a 4th order Butterworth filter. A pass band of 5-25 Hz was used for antero-posterior and left-right components, while a pass band of 1-30 Hz was used for the head-to-foot component [9].

2.4. Heart rate variability

An automatic beat identification method was applied on each of the 6 inertial channels of the SCG signal. The method, described in [9], consists in the identification of a 400-ms template centred at the maximum point within the first 10 seconds of signal. The cross-correlation of the template with the signal was then computed and used to identify the points of maximum local amplitude, which corresponded to the aortic valve opening (AO) point [10]. Afterwards, inter-beat interval duration (AO-AO) series were computed as an index of heart rate. The component associated with minimum mean squared deviation of the AO-AO series with respect to a 5th order polynomial fitting the data was selected among the 6 inertial channels for further analysis [9]. On this component, ultra-short heart rate variability (HRV) analysis was performed. The standard deviation of the inter-beat intervals (SD_{AO-AO}) and the root mean square of successive difference of AO-AO intervals (RMSSD) were computed. Additionally, the SD_{AO-AO} /RMSSD ratio was calculated as an indicator of the sympatho-vagal balance [11].

2.5. Morphological analysis

The morphological analysis was performed on the z-axis of the accelerometer, resulting the most accurate component in most of the acquisitions. For each acquisition, a median template representing the SCG waveform of one beat was computed, on which isovolumetric contraction (IVC), aortic valve opening (AO) and aortic valve closure (AC) points were identified [9,10]. The temporal intervals between IVC and AO (t_{IVC-AO}), and between IVC and AC (t_{IVC-AC}) were calculated. Finally, the IVC-AO amplitude (AMP_{AO-IVC}), the ratio of AO and AC amplitude (AMP_{AO}/AMP_{AC}), and the slope between IVC and AO were computed.

2.5. Kinetic energy

The linear and rotational kinetic energies (respectively K_{lin} and K_{rot}) generated from cardiac activity were computed as in [8]:

$$k_{lin} = \frac{1}{2}m(v_x^2 + v_y^2 + v_z^2) \quad (1)$$

$$k_{rot} = \frac{1}{2}m(I_{xx}w_x^2 + I_{yy}w_y^2 + I_{zz}w_z^2) \quad (2)$$

where m (kg) is the mass of the subject, v (m/s) is the velocity derived from linear accelerations by single-time integration, w (rad/s) is the angular velocity measured from the gyroscopes and I_{xx}, I_{yy} and I_{zz} are the orthogonal components of the moment of inertia calculated using a model of human body moments of inertia that only requires the height and weight of the subject [12]. The changes in participants' height and weight at BR10 and R+1 due to BR were taken into consideration. The integral of k_{lin} (ik_{lin}) and k_{rot} (ik_{rot}) over each cardiac cycle was computed and the median value was calculated, as well as their sum and ratio.

2.6. Statistical analysis

In order to evaluate the possible deconditioning induced by 10-days BR in the computed temporal,

morphological and kinetic energy parameters, BR10 and PRE were compared. Also, to verify the return to baseline values after the reinstatement of the orthostatic posture, values at R+1 were compared to PRE. Finally, to evaluate the effect of perceived deconditioning at the reinstatement of the orthostatic posture, BR10 was compared to R+1 values. The Wilcoxon Signed Rank test was applied for comparisons, and the level of significance was set to 0.05.

3. Results

Results are reported as median [25th percentile; 75th percentile].

3.1. Heart rate variability

The results of the median AO-AO and ultra-short HRV analysis are shown in Figure 1. The median AO-AO exhibited a progressive decrease compared to PRE, which appeared significant at R+1 (-13.9[-19.6;-6.1]%). The SD_{AO-AO}/RMSSD ratio increased at BR10 compared to PRE (+49.5[2.2;71.3]%), and then only partially recovering at R+1 (+15.5[-5.3;30.9]%).

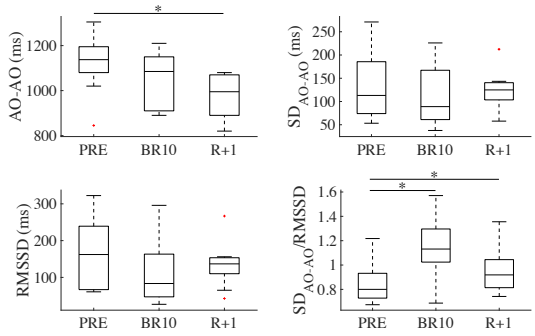

Figure 1. Distribution of median AO-AO and HRV indices at PRE, BR10 and R+1. *: Wilcoxon Signed Rank test, p-value < 0.05.

3.2. Morphological analysis

Table 1 reports the results of the morphological analysis. In particular, the AMP_{AO-IVC} increased at BR10 compared to PRE (+36.9[0.3;69.9]%), then decreasing at R+1 compared to BR10 (-28.4[- 36.1;-11.1]%). Also, the AMP_{AO}/AMP_{AC} ratio and IVC-AO slope partially increased at BR10, although not significantly. Afterwards, the AMP_{AO}/AMP_{AC} decreased at R+1 compared to BR10 (-35.2[-54.2;-19.5]%), and as well the IVC-AO slope (-39.5[-52.1;-22.7]%). The temporal intervals t_{IVC-AO} and t_{IVC-AC} remained unaltered.

Table 1. Results of the morphological analysis at baseline (PRE), after 10 days of BR (BR10), and one day after reambulation (R+1).

	PRE	BR10	R+1
t_{IVC-AO} (ms)	30[20;50]	30[20;60]	45[30;60]
t_{IVC-AC} (ms)	370[350; 380]	360[340; 370]	360[340; 362.5]
AMP_{AO-IVC} (g)	0.02[0.02; 0.03]	0.03[0.02; 0.04] *	0.02[0.02;0.03] #
AMP_{AO}/AMP_{AC}	1.37[0.66;1.80]	1.60[1.31;2.02]	1.39[0.83;1.58] #
IVC-AO slope	0.63[0.53;1.28]	0.98[0.42;2.02]	0.50[0.33;0.85] #

*: epoch vs PRE (Wilcoxon Signed Rank, p-value<0.05)
#: epoch vs BR10 (Wilcoxon Signed Rank, p-value<0.05)

3.3. Kinetic energy

The results of the linear and rotational kinetic energy are reported in Figure 2. The ik_{lin}/k_{rot} ratio increased at R+1 when compared to PRE (+213.2[26.2;247.0]%) and to BR10 (+185.4[-11.1;444.7]%).

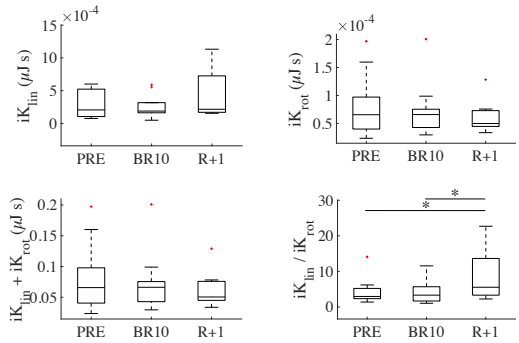

Figure 2. Distribution of ik_{lin}, ik_{rot}, their sum and their ratio at PRE, BR10, and R+1. *: Wilcoxon Signed Rank test, p-value < 0.05.

4. Discussion

To the authors' knowledge, this is the first study investigating the possibility to exploit short-duration smartphone-SCG acquisition for monitoring cardiac electro-mechanical deconditioning induced by horizontal BR. Standard heart rate and HRV analysis was performed in parallel to the computation of novel biomarkers, including SCG morphology and kinetic energy parameters.

In a previous work [9], we demonstrated the possibility to capture expected alterations in the autonomic control of heart rate in response to specific stimuli by means of smartphone-acquired SCG signals assessing the ability to discriminate between a state of relaxation and a state of stress induced by a mental computation task. Following the results of [9], ultra-short HRV methods were applied in this work. Short (1-minute) SCG signals were acquired

by positioning a smartphone on subject's sternum within 30 minutes of awakening. Being associated with an increased risk of cardiac events [13], the first hours after morning awakening are particularly informative of cardiac health condition. In this study, the AO-AO interval tends to decrease both at BR10 and, significantly, at R+1 compared to PRE. As the AO-AO interval is inversely related to the heart rate, these results indicate that the heart rate at awakening increases at BR10. At the same time, the $SD_{AO\text{-}AO}$/RMSSD ratio increased, suggesting a shift towards sympathetic modulation of the heart activity at early morning, a condition that has been related to an increased risk of adverse cardiovascular events [14].

Despite the described increase of the AO-AO interval at BR10 and R+1, no changes were observed in the time intervals between IVC, AO and AC peaks. This suggests that the observed increase of the AO-AO interval may potentially be attributed to the passive phase of ventricular diastole (i.e., diastasis). The SCG amplitude has been proposed as an estimator of the stroke volume [15]. Suggesting an increase in the IVC-AO peak-to-peak at BR10, our results appear in contrast with the observation of a reduction in stroke volume after prolonged BR [2]. However, its opposite changes at R+1, together with IVC-AO slope, reflect variations in the hemodynamic status.

Finally, the sum of ik_{lin} and ik_{rot} is representative of the total kinetic energy that is generated by the heart at cardiac contraction and transmitted to the chest. Ten days of horizontal bed rest did not induce significant alterations in the total kinetic energy. However, the increased ik_{lin}/k_{rot} at R+1 denoted a decreased contribution of the rotational component over the total kinetic energy, in agreement with what observed after 60 days of head-down (-6°) BR [16].

5. Conclusions

Prolonged horizontal bed rest affects cardiac electro-mechanical activity in healthy subjects. Future works should compare the present findings with changes in blood pressure induced by bed rest. This analysis could improve the interpretation of the results, providing important insights in the involved physiological processes.

Acknowledgments

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