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A Wearable System for the Seismocardiogram Assessment in Daily Life Conditions

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Abstract— **Seismocardiogram (SCG) is the recording of the minute body accelerations induced by the heart activity, and reflects mechanical aspects of heart contraction and blood ejection. So far, most of the available systems for the SCG assessment are designed to be used in a laboratory or in controlled behavioral and environmental conditions. In this paper we propose a modified version of a textile-based wearable device for the unobtrusive recording of ECG, respiration and accelerometric data (the MagIC system), to assess the 3d sternal SCG in daily life. SCG is characterized by an extremely low magnitude of the accelerations (in the order of g x 10^{-3}), and is masked by major body accelerations induced by locomotion. Thus in daily life recordings, SCG can be measured whenever the subject is still. We observed that about 30 seconds of motionless behavior are sufficient for a stable estimate of the average SCG waveform, independently from the subject's posture. Since it is likely that during spontaneous behavior the subject may stay still for at least 30 seconds several times in a day, it is expected that the SCG could be repeatedly estimated and tracked over time through a prolonged data recording. These observations represent the first testing of the system in the assessment of SCG out of a laboratory environment, and open the possibility to perform SCG studies in a wide range of everyday conditions without interfering with the subject's activity tasks.**

I. INTRODUCTION

SEISMOCARDIOGRAM (SCG) is the recording of the minute body accelerations induced by the heart activity [1,2]. The high frequency component of the seismocardiographic signal mainly reflects the closure of the cardiac valves [3], while the low frequency component is related to vibrations induced by the blood flow ejection into the vascular bed [4,5]. The latter component is also referred to as ballistocardiogram (BCG), although this term is sometimes used to indicate the whole seismocardiographic signal, i.e. both the low and high frequency vibrations.

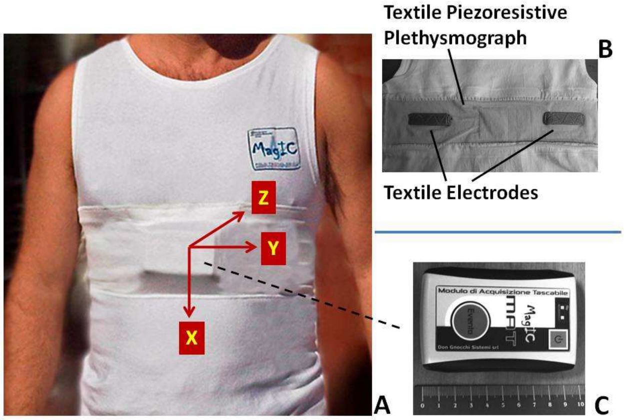

Fig 1 - *Panel A:* The MagIC vest with orientation of the accelerometric axes: x (longitudinal, head-foot), y (lateral, right-left) z (ventro-dorsal, front-back). *Panel B*: The inner part of the vest with the textile electrodes and the piezoresistive plethysmograph. *Panel C*: Particular of the electronic board inserted in the vest pocket.

From the interpretative perspective, the electrocardiogram (ECG) represents the sequence of *electrical* events occurring in the heart, while SCG reflects some of the *mechanical* aspects involved in the heart contraction and blood ejection. The traditional interpretation of the waves occurring in the BCG signal at each heart contraction is reported in Fig.4. It has been suggested that additional information (including the quantification of stroke volume) can be derived from the SCG signal, although further studies are required to fully explore the potentiality of this signal in reflecting cardiovascular mechanics.

SCG and BCG became popular from the forties to the sixties. However, at that time the complexity of the measurement devices limited the use of these signals to research laboratories. Recently, the interest in SCG has been revitalized by the availability of wearable MEMS sensors, which make the assessment of body accelerations simple and unobtrusive. So far most of the available systems for the SCG assessment are designed to be used in a laboratory or in controlled behavioral and environmental conditions. Now, through the use of a textile-based wearable system (the MagIC System), it is possible to obtain the integrated assessment of SCG (including the BCG component) and other vital parameters during spontaneous behavior in daily life settings. This approach allows us to explore for the first time how the SCG features are modified by the daily activities and how SCG dynamics is correlated with other biological signals. In this system, a single 3d accelerometer can detect major accelerations resulting from motion

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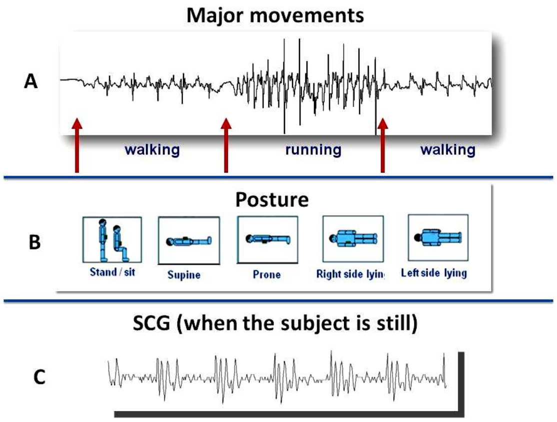

Fig. 2 Information derivable from the accelerometric data of the system.- *Panel A*: Major movements (including walking and running.). *Panel B*: Posture. *Panel C*: SCG while the subject is still (100x magnification). Modulus of the 3d acceleration is displayed in panel A, accelerometric z component is displayed in panel C.

activities and, whenever the subject is still, the SCG. The latter can be detected independently from the posture of the subject.

The architecture of the device presented here is based on previous laboratory tests in which we investigated the feasibility of detecting SCG through a textile-derived ECG and an external accelerometer positioned on the clavicle [6].

In the present paper we briefly illustrate the structure of the MagIC system along with the characteristics of the collected SCG signal and provide data samples showing the applicability of this approach to assess SCG in different daily life contexts, out of the laboratory setting.

The System

A. The MagIC device

Details on the MagIC system, its validation and applications in clinical and non-clinical areas have been previously provided [7, 8, 9]. Here, we only present a short summary of its characteristics and applications.

The whole system is composed of a textile vest and an electronic board (see figure 1). The vest is mainly made of cotton and elastan. In the inner part, at the thorax level, it includes two textile electrodes for the assessment of one ECG lead. Just below these sensors there is a textile piezoresistive plethysmograph capable of detecting variations in the thorax circumference over time from which the respiratory rate is derived, (fig 1, panel B). All signals reach a small electronic board (fig 1, panel C) through textile conductive pathways embedded in the vest. In this version of the system, the electronic board is positioned inside an elastic pocket of the vest located at the sternum level (while in the standard system the electronic board is positioned on the right side of the vest). This board includes a 3d accelerometer (ST LIS3LV02DL, ±2g, 12bit), a secure digital memory card for local data storage, and a Bluetooth transmitter for real time connections with external devices.

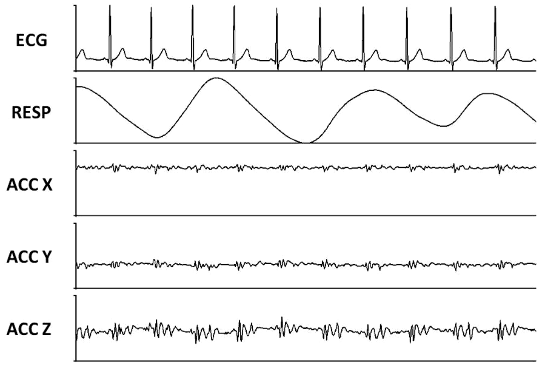

Fig. 3 Example of data collected in a standing subject. Depicted signals (top to bottom): electrocardiogram, respiration and x, y and z accelerometric component of SCG.

The system has been extensively used to monitor vital signs in cardiac patients, elderly people and healthy subjects (the latter during physical exercise, at high altitude, during parachute jumps, parabolic flights and jet flight maneuvers characterized by abrupt gravitational changes).

B. Accelerometric data

As shown in figure 2, the 3d accelerometer of the system can provide three different pieces of information: a quantification of major movements (including walking and running), posture (standing/sitting, lying), and, whenever the subject is still, the SCG signal. In particular, given the position of the electronic board, the system detects a *3d sternal SCG acceleration.* The orientation of the accelerometer axes are shown in figure 1 panel A.

An example of the three SCG accelerometric components in a supine subject is provided in fig 3.

II. Signal processing issues

A possible approach for the analysis of the SCG signal is based on the preliminary estimation of an average SCG

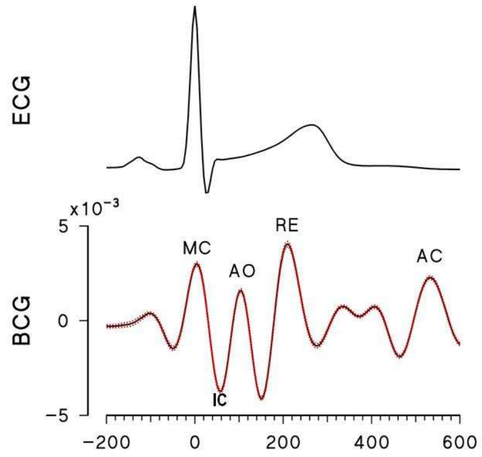

Fig.4 - Example of average waveforms of ECG and low frequency component of SCG (BCG). Main BCG waves are annotated as proposed in [11]: MC= Mitral valve Closure, IC= Isovolumetric Contraction, AO= Aortic valve Opening, RE= Rapid ejection, AC= Aortic valve closure

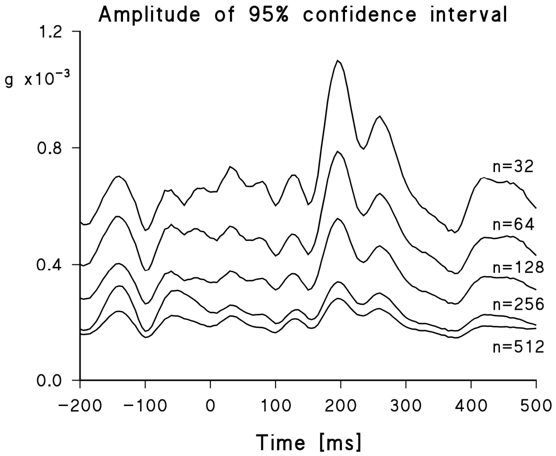

Fig 5 - 95% confidence limits in the estimation of the average SCG wave as a function of the number of heart beats

waveform over a given time window, followed by a pattern analysis of the resulting averaged waveform. The ECG R peak is usually taken as the fiducial point for the time alignment of the SCG waveforms (see example in fig. 4). The generic processing of the low frequency component of SCG was previously described [6], while the analysis of the high frequency SCG components as obtained by the MagIC system is described in another paper proposed at this conference [10]. Here we preliminary investigated in one subject how the number of beats considered for the averaging might influence the estimate of the SCG waveform, particularly for its low-frequency component, i.e. the ballistocardiogram.

To this aim, we considered a 512-beat data segment recorded in a healthy supine subject in a stationary condition. From these data we computed the 95% confidence interval in the estimation of the average BCG waveform, obtained by using windows sizes of 512, 256, 128, 64 and 32 beats. The results of the analysis are reported in fig. 5.

The BCG waveforms averaged over window sizes from 32 to 256 beats were also plotted in a superimposed fashion in fig. 6. From these data it is apparent that even a 32 beat window provide a relatively stable BCG waveform, with discrepancies in the order of 5%. These data suggest that about 30 seconds of stable signal might be sufficient to obtain a reliable BCG (and likely SCG) estimate.

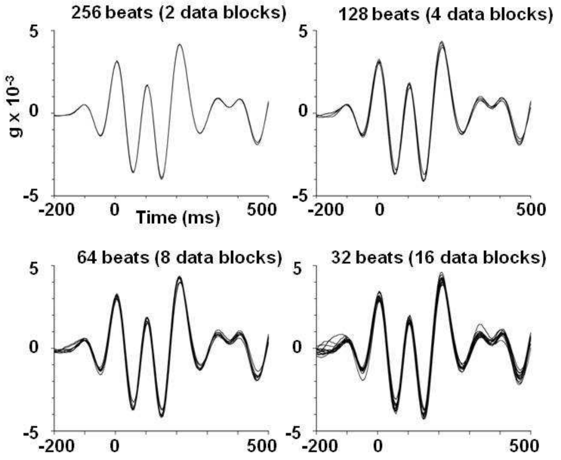

Fig. 6 -Superimposition of low frequency SCG waveforms (the ballistocardiogram) estimated by different window lengths (256, 128, 64 and 32 beats).

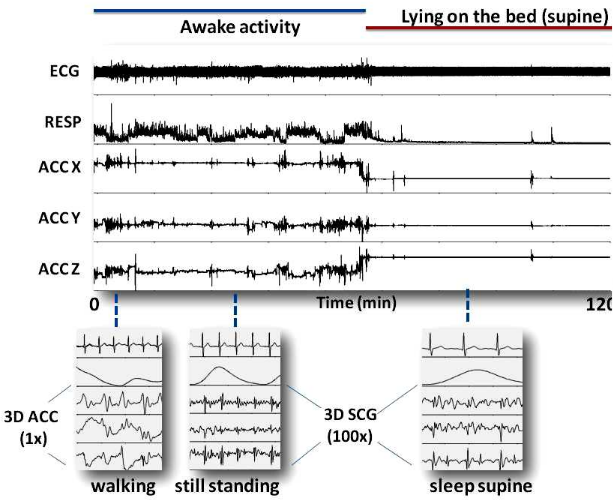

Fig. 7 Two-hour segment of data recorded by the MagIC system in a subject during spontaneous awake activity and while sleeping in supine position on the bed. Lower insets illustrate information derived by the 3d accelerometer while walking, during still standing and while sleeping.

III. APPLICABILITY IN REAL LIFE CONDITIONS

Hereafter, three examples of applicability of this approach out of the laboratory setting are provided.

Figure 7 shows how SCG can be monitored in different spontaneous behavioral conditions. In this figure, it is shown a two-hour data segment recorded in a subject at night. In the first recording hour, the subject was still awake and moving around. The accelerometer detected the major movements (mostly walking, in this case) and the 3d SCG signal whenever the subject was standing still. Subsequently, the subject went to bed and the SCG was detected almost continuously.

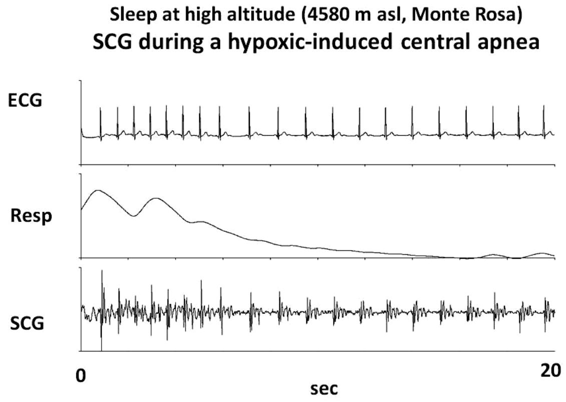

Fig. 8. ECG, respiration and accelerometric z component of the Seismocardiogram (SCG) during a sleep central apnea in a subject exposed to high altitude hypoxia.

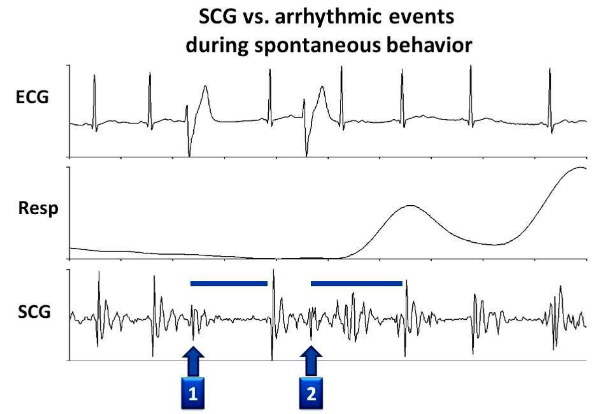

Fig 9 - ECG, respiration and accelerometric z component of the Seismocardiogram (SCG) during arrhythmic events. Arrows and horizontal bars indicate SCG waveforms produced by ectopic events that modify (#1) and do not modify (#2) the rhythm regularity.

The MagIC device might also be used to investigate sudden changes in the SCG waveform in response to fast specific events, lasting at most few seconds. Obviously in these cases the SCG cannot be averaged, and the features of interest should be extracted from a single waveform. Figure 8 shows an example of the SCG behavior in a healthy subject during sleep at high altitude, while a hypoxia-induced central apnea occurs. It can be noted how different phases of the apnea, known to importantly modify the cardiovascular mechanics, are reflected by marked changes in the structure of the SCG waveform.

A second example of the system ability to catch dynamic changes in the SCG waveform is illustrated in figure 9. In this case the recording was performed in a subject experiencing arrhythmic episodes during the day. The mechanical and hemodynamic effects resulting from the occurrence of premature contractions are reflected by changes in the SCG waveforms. The structure of these changes appears to be different according on whether the ectopic event influenced (fig 8, arrow #1) or did not influence (fig. 8, arrow #2) the rhythm regularity.

IV. Discussion and Conclusions

In this paper we proposed a modified version of the MagIC system, a textile-based wearable device for the unobtrusive recording of vital data, to measure the sternal SCG in daily life.

This study represents the first testing of the system in the assessment of SCG out of a laboratory environment. Our positive observations open the possibility to assess SCG (and thus derive information on the cardiovascular mechanics) in a wide range of conditions almost without interfering with the subject’s activity and independently from his/her posture. We observed that in our test subject about 30 seconds of motionless behavior were sufficient for a stable estimate of the average SCG waveform (at least for the BCG component). During spontaneous behavior the subject is likely to stay still for at least 30 seconds several times in a day, thus our finding, to be confirmed in a larger population, suggests that the SCG might be repeatedly estimated and tracked over time through a prolonged data recording. This would allow the analysis of SCG as a function of the posture (standing/sitting vs. supine) during daytime recordings, or of different body positions when sleeping at night.

Additionally, the simultaneous recording of other physiological signals (ECG and respiration), currently featured by the MagIC device, might further facilitate the analysis and interpretation of SCG results. For instance, the available information on the inspiratory and expiratory phases of breathing (through the textile plethysmograph) can greatly simplify the quantification of respiratory related modulations in SCG, which have been previously reported to characterize the ballistocardiographic tracings in space [12].

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