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Three dimensional ballisto- and seismo-cardiography: HIJ wave amplitudes are poorly correlated to maximal systolic force vector.

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Abstract—**Ballistocardiography was recorded in 3-D on a free floating astronaut in space as well as on healthy volunteers participating to the ESA 55th and DLR 19th parabolic flights campaigns. In this paper we demonstrate further the usefulness of recording and analyzing ballistocardiograms (BCG) in three dimensions. The spatial curves of the displacement, velocity and acceleration vectors are analyzed instead of their individual 2-D components. The maximum magnitude of the force vector is shown to be poorly correlated to the HI and IJ wave amplitude traditionally computed on the longitudinal (feet-to-head) component of acceleration (uni-dimensional BCG). We also suggest that kinetic energy and work are useful parameters to consider for a physiological interpretation of the 3D-BCG. The technique presented is invariant from the axis of representation and provides important novel physiological information. We stress further the need of 3D recordings and analysis techniques for Ballisto- and Seismo-cardiography.**

I. INTRODUCTION

BALLISTOCARDIOGRAPHY (BCG), in our day-to-day terrestrial environment, is typically studied on subjects lying on a table, sitting on a chair, or standing on a scale. These devices are equipped for the monitoring of forces, accelerations, velocities or displacements. In the vast majority of cases, the research is limited to 1D or 2D analysis of BCG components in the frontal plane and most of the physiological interpretations are drawn from the component along the longitudinal (foot-to-head) axis. Since the early days of the Ballistocardiography, attempts were made to record a vecto-ballistocardiogram, i.e. a simultaneous recording of the accelerations or forces in the 3-dimensions (3-D) of space [5]. These attempts were scarce and never largely embraced. Indeed, the influence of gravity along the vertical axis, presents a technical challenge and forbid the study of physiological properties in isotropic conditions. Hence since the beginning of the space exploration era attempts to record 3D-BCG in microgravity were made [1,2,3]. In a previous work [3,4] we reported results from a data set of 3-D BCG which was recorded in 1993 on a crew member of the Spacelab-D2 mission. The description of the BCG along three axes revealed that the information along the antero-posterior axis was of comparable magnitude as the 2 others [3]. We developed further a set of numerical methods to perform a 3-D analysis of the BCG curves [4], providing numerical information that is independent from the choice of a reference axis. In the present paper we compare the HI and IJ amplitudes, formerly used as marker of cardiac contraction efficiency, with the maximum magnitude of the force vector.

Results from Spacelab-D2 data (sustained microgravity) are presented together with results from the ESA 55th and DLR 19th parabolic flight campaigns (transient microgravity) conducted on-board the A300-zéroG airplane of NOVESPACE.

Our results show that the amplitudes of the HI and IJ waves are poorly correlated to the maximum magnitude of the force vector in the systolic phase. Therefore the use of these parameters could be misleading for a physiological interpretation. Moreover, data recorded in transient microgravity and in sustained microgravity show important similarities, thus suggesting the generalizability of these results.

II. PROTOCOLS AND EXPERIMENTAL PROCEDURES

A. Sustained microgravity data

The BCG along the three anatomical orthogonal axes (using a triaxial accelerometer), the respiratory movements of the ribcage and the abdomen (using respiratory inductance plethysmography), as well as the electrocardiogram (ECG) were recorded in one subject in sustained microgravity, over a period of 15 min. Respiration, ECG and BCG signals were sampled at 50 Hz, 500, and 300 Hz respectively and were up-sampled at the lowest common multiple frequency 1500 Hz using a low-pass cubic-spline interpolation algorithm. The technical details are fully described in [3]. In brief: the longest uninterrupted period of the recording, during which no contact with the Spacelab structure or with the other astronauts occurred (verified from a video recording), a continuous 176 s period was used. During this period, no significant rotation was observed. Consequently, acceleration data represent only linear accelerations.

B. Transient microgravity data

3-D accelerations together with ECG, Impedance

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cardiogram (ICG) and respiration signal (nasal thermistor) were recorded, at 1kHz using a modified PNEUMOCARD system [4]. 4 healthy subjects were free-floating during the ~20s of microgravity phases obtained during the parabolic maneuver of the A300-ZéroG airplane of NOVESPACE. Sensor was placed either at the center of mass (CM) of the subject in order to provide a 3D-BCG or at the apex of the heart to provide a three dimensional Seismocardiogram (SCG) signal. Results presented here are only from one of the 4 subjects.

C. *Ethical approval*

The protocols were non invasive and reviewed and approved by the respective institutional ethical review boards, and informed consent of the subjects were obtained.

D. *Axis System*

We chose to use the nomenclature for the axes that is the standard in ballistocardiography, where *x* is the lateral (left-to-right) axis, *y* is the longitudinal body (foot-to-head) axis, and *z* is the antero-posterior (ventro-dorsal) axis.

III. METHODS

A. *Ensemble averaging*

R waves of the ECG were automatically identified, visually inspected, and edited if required. Timings of the R waves were used as reference points to identify each cardiac cycle. For each cycle, the ECG and BCG data were sliced and represented as function of a normalized time axis: the beginning of each cycle was set to 0 and the end to 1000. Normalized curves of the ECG and BCG from different heart-beats were superimposed and ensemble averaged to compute BCG and ECG signals (see Fig. 1). This procedure allowed ensemble averaging in the presence of the normal heart rate variability.

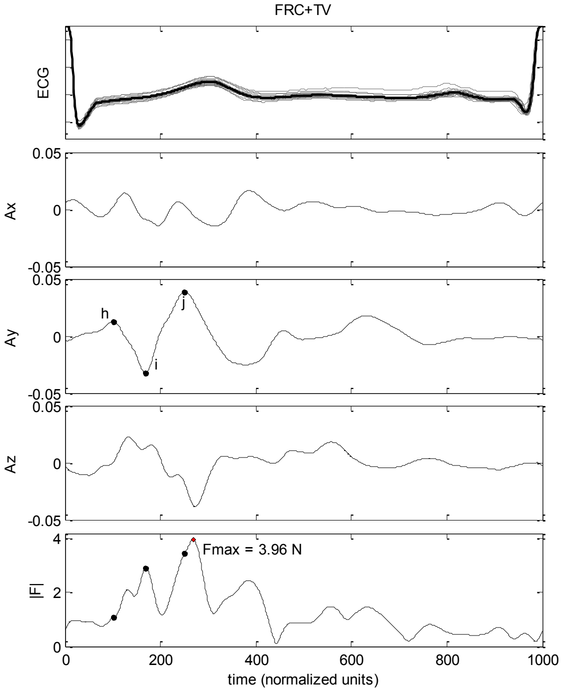

Fig. 1. From top to bottom: beat-by-beat ECG with ensemble averaged trace; projections of the BCG accelerations on the 3 anatomical axes (left to right (x), feet to head (y), antero-posterior (z) in m/s^2); Force vector (in Newton); h i j waves are marked by a black dot on the Acc Y axis as well as on the Force vector.

B. *Drift removal*

According to Newton's second law of motion, for a body at rest and in absence of external forces, after one cardiac cycle, all components of the acceleration, velocity and displacement vector should be back to their initial position. However, in order to get such an ideal representation, accelerations due to respiration and to other movements, not correlated with the heart-beats, should be removed. We used a low pass filtering technique applied in the frequency domain.

C. *Acceleration vector*

Figure 1 presents the 3 components of acceleration together with the magnitude of the force vector computed as:

$$\left|\vec{F}\right| = m \cdot \sqrt{a_x^2 + a_y^2 + a_z^2} \qquad (1)$$

where m is the mass of the subject (81 kg for the D2 astronaut). The curves were computed for heart beats occurring at functional residual capacity (FRC, end-expiration, 31 beats), and at the end of inspiration, FRC + tidal volume (FRC+TV, 40 beats). The FRC+TV data set (Fig. 1) is used to further illustrate the method. Localization of the H I J waves from the Y axis component are displayed on the Y-axis component and the magnitude of the Force vector.

D. *Velocity and Kinetic Energy*

Components of velocity are computed as the integral of the acceleration components and kinetic energy is given by:

$$K = \frac{1}{2} m \cdot \sqrt{v_x^2 + v_y^2 + v_z^2} \qquad (2)$$

Kinetic energy of the same data set of Fig.1 is presented in Fig. 2 with the ECG and other parameters. It is seen that K present a large peak just after the main peak in the magnitude of the force vector.

E. *Displacement and Work of the force*

Components of displacement are computed as the integral of the velocity components and Work is given by:

$$dw = d\vec{F} \cdot d\vec{r} \qquad (3)$$

where $d\vec{F}$ denotes the increment of force and $d\vec{r}$ is the increment of the vector position. Magnitude of the instantaneous displacement and work of the force are seen on Fig. 2 together with force and kinetic energy. It is seen that the maximum displacement occurs during the diastolic phase while work present maxima when either the force or the displacement vector are large.

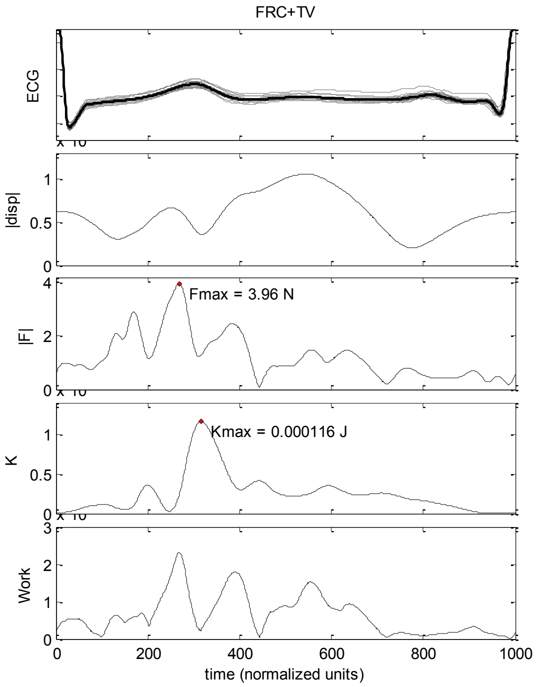

Fig. 2. From top to bottom: beat-by-beat ECG; magnitude of displacement (10^{-4} m); magnitude of Force (N); Kinetic energy (10^{-3} J); Work (10^{-4}J). Work presents large values (peaks) in systolic as well as diastolic phases; when either Force or displacement presents large values.

IV. TRANSIENT MICROGRAVITY

Data presented on Fig. 3 are from the ensemble averaging of 3D-accelerations from 8 heart beats recorded at the CM (BCG signal) of a free-floating subject. Data presented on Fig. 4 are from the ensemble averaging of 3D-accelerations from 17 heart beats recorded at the apex of the heart (SCG signal) during the longest uninterrupted recording in the same subject. On Fig.4 it is noticeable that the peaks in force, kinetic energy and work comes much closer to the QRS complex of the ECG and before the large peak of the ICG curve which is a signal proportional to stroke volume. This suggests that SCG signal reflect a physical activity of the heart that comes before the ejection phase which is different from the BCG signal where the main peaks in force and kinetic energy come noticeably later and more in phase with the ejection of blood in the aorta.

During parabolic flight the microgravity phase is preceded by a hypergravity phase of about 1.8g during about 15s. This has a large influence on the cardiovascular system: there is a pooling of blood in the lower part of the body and during the early phase of microgravity the blood return to the heart is increased. This in turn produces an increased filling of the right heart and conditions that are highly transients.

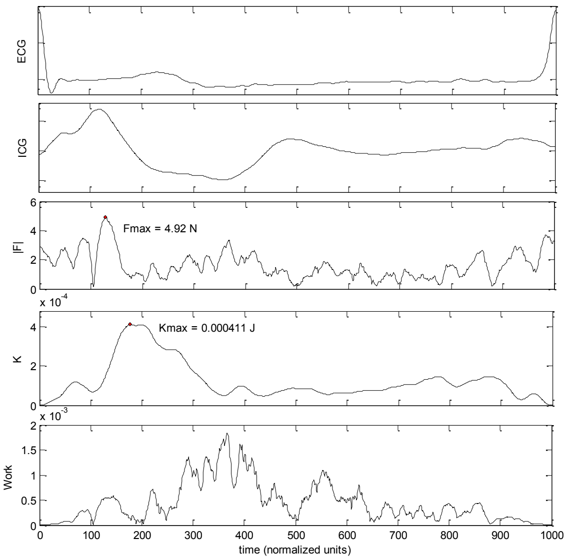

Fig. 3. From top to bottom: ECG (a.u.); ICG (a.u.); Force (N); Kinetic Energy (10^{-4} J); and Work (10^{-3}J) from a BCG recording (sensor at CM) during the microgravity phase of a parabolic flight maneuver.

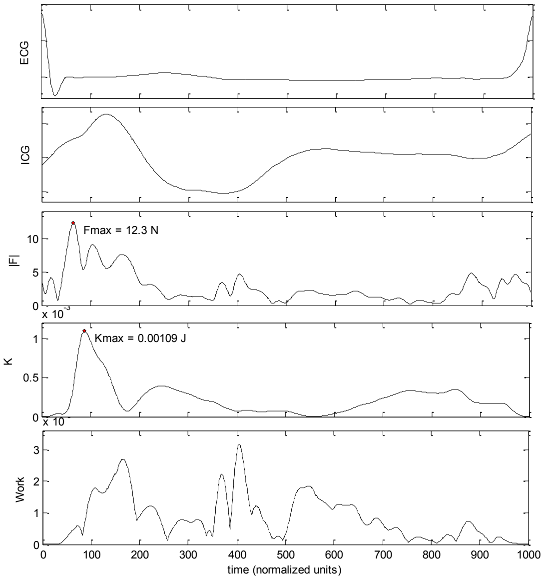

Fig. 4. From top to bottom: ECG (a.u.); ICG (a.u.); Force (N); Kinetic Energy (10^{-4} J); and Work (10^{-3}J) from a SCG recording during the microgravity phase of a parabolic flight maneuver.

V. AMPLITUDES OF THE HI & IJ WAVES

We used the 176 heart-beat recording from the Spacelab-D2 data set to study the correlation between the amplitudes of the HI (Fig. 5) and IJ (Fig. 6) waves and the magnitude of the maximum of the acceleration vector.

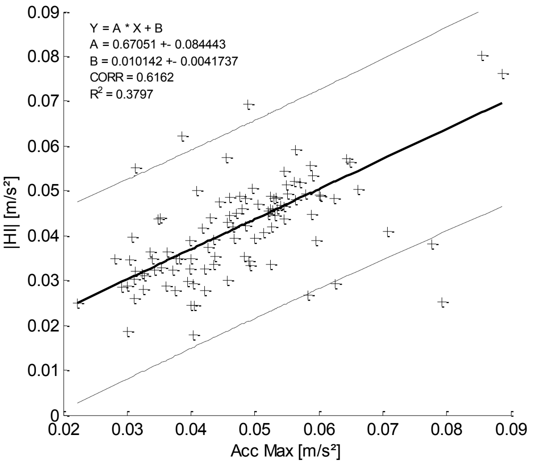

Fig. 5. Correlation between amplitude of the HI wave and the maximum of the magnitude of the acceleration vector for the BCG recording of the Spacelab-D2 experiment.

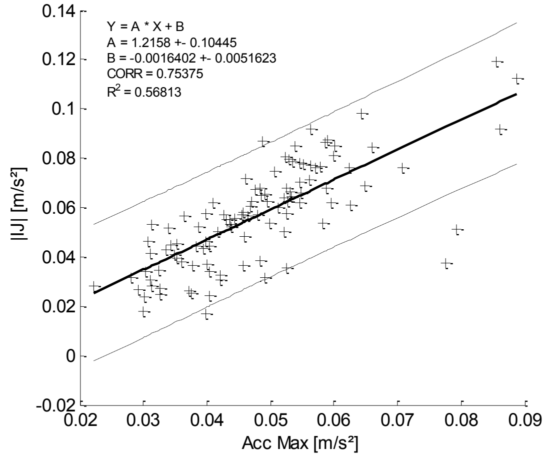

Fig. 6: Correlation between amplitude of the IJ wave and the maximum of the magnitude of the acceleration vector for the BCG recording of the Spacelab-D2 experiment.

Correlations are rather low, R^2 are respectively 0.38 and 0.57 for HI and IJ waves respectively. This is very low for the wave amplitudes that were supposed to measure the force generated during the cardiac contraction.

CONCLUSION

Our results show that both in sustained and transient microgravity the 3D analysis of BCG or SCG curves provide consistent results: a maximum in the force vector which is followed by a maximum in kinetic energy and peaks in the work of the curve. The differences seen between the SCG and BCG curves recorded in parabolic flight on the same subject are not surprising. Indeed, the localization of the sensor on the apex of the heart, i.e. very close to the source of the force, is supposed to create a signal in advance to the components recorded at the center of mass of the subject. This shows that the terminology used for the naming of the BCG waves should probably not be used to describe the waves seen in the SCG signal. Indeed, it is likely that they represent a different physiological phenomenon. Finally that there is a poor correlation between the amplitude of the waves observed on the longitudinal (foot-to-head) axis and the magnitude of the force vector demonstrates further that past assumptions and physiological interpretation of these waves were misleading. This also strongly suggests that for a physiological interpretation of BCG and SCG signals a 3D analysis of the acceleration or force vector is required.

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