Standing Ballistocardiography Measurements in Microgravity

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***Abstract*— The performance and practicality of a scale-based ballistocardiogram (BCG) system for hemodynamic monitoring of astronauts on extended space missions was demonstrated. The system consists of a modified electronic weighing scale fitted with foot bindings to mechanically couple the subject to the scale. This system was tested on a recent series of parabolic flights in which scale-based and accelerometry-based free-floating BCG of 10 subjects was measured in microgravity. The signal-to-noise ratio (SNR) of the scale-based BCG was, on average, a factor of 2.1 (6.3 dB) higher than the free-floating method, suggesting that the tethered scale approach might be more robust in terms of signal quality. Additionally, this approach enables practical BCG-based hemodynamic monitoring in fractional-g environments, and on small space vehicles such as NASA's upcoming Orion capsule. The scale-based results in microgravity were also compared to ground measurements (1g), where there was an average 38.7 ms RJ interval reduction from ground to microgravity environments that is consistent across 9 of 10 subjects. This phenomenon is likely due to the transient increase in venous return, and consequent decrease in pre-ejection period, experienced during the microgravity time intervals.**

I. Introduction

Prolonged exposure to microgravity forces the body's hemodynamic control system to adapt in order to maintain homeostasis in the absence of the hydrostatic pressure induced by gravity. If this adaptation is not identified and counteracted, extensive post-spaceflight reconditioning may be required to treat microgravity-induced conditions such as hypovolemia or postflight orthostatic intolerance [1, 2]. These conditions have been reported in astronauts after spaceflights as short as 3 days, and worsens as the duration of the flight increases [3]. Therefore, it is important to monitor cardiovascular deconditioning in medium- to long-duration spaceflights in order to take appropriate countermeasures before returning to Earth.

The ballistocardiogram (BCG) is a noninvasive device capable of measuring the force due to the ejection of blood by the heart with each heartbeat [4]. It has been clinically verified that features of the scale-based BCG, such as the RJ interval, are capable of monitoring many relevant cardiac parameters such as cardiac output changes, contractility changes, central pressures, and arterial stiffening [5-8]. On a spacecraft, this scale can be mounted on a floor or wall with foot binding straps to secure the astronaut in place for convenient measurement.

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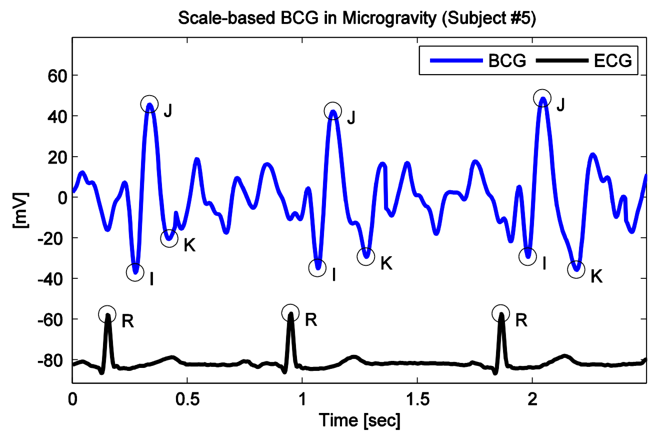

Fig. 1. Scale-based standing BCG recorded in microgravity. Each beat is ensemble averaged between the 6 adjacent beats using ECG R-wave peaks as fiducials. These R-wave peaks and the IJK complex of each BCG beat are marked. The RJ interval is defined as the time between corresponding R-wave and J-wave peaks.

The feasibility of a multi-gravity (multi-g) system for space applications was demonstrated in a preliminary study [9], where scale-based BCG measurements were taken on the ground and in microgravity during a separate series of parabolic flight maneuvers. Results from the preliminary study suggested that certain timing parameters, specifically the RJ interval, may be influenced by microgravity. In this study, microgravity effect on the RJ interval timing differences was further analyzed for 10 human test subjects, each engaging in 14-20 parabolic maneuvers. For each subject, scale-based BCG was measured on the ground and in microgravity, and accelerometry-based BCG was measured while free-floating in microgravity. Fig. 1 shows a typical scale-based BCG measured while standing in microgravity.

Previous works on microgravity BCG measurements have been focused on triaxial accelerometry-based methods that require the subject to be suspended in a weightless free-float [10, 11], or by dry immersion [12]. Free-floating BCG measurements, however, are impractical to measure in a confined spacecraft, such as NASA's Orion capsule (under development) where astronauts cannot free-float without colliding with equipment or other crewmembers. The free-floating method is also challenging to use in fractional-g environments such as the Moon or Mars. A comprehensive review of alternative methods is given in [13]. The scale-based system addresses these issues by providing a robust solution for multi-g BCG recordings using the same platform that has been validated through several clinical studies on Earth and in microgravity environments.

Fig. 2. Experiment setup for scale-based (left) and free-floating measurements (right). The scale was secured to the aircraft by a compressing crossbar mounted to a vibration-isolated metal plate on the aircraft frame. Free-floating subjects were manually restrained by team members.

The methods, system design, results, and analysis are discussed in the following sections.

II. Methods

A BCG scale validated in human subject testing [6] was adapted for a microgravity environment and tested aboard a Boeing 727-200 aircraft (Zero Gravity Corporation, Vienna, VA) while performing a set of parabolic maneuvers. The study took place at NASA's Reduced Gravity Office, Johnson Space Center (Ellington Field), Houston, TX, with human subject test protocols approved by the NASA and Stanford University Institutional Review Boards (IRB) protocols #CR00000337 and #24294 respectively.

A. *Microgravity BCG System*

This hardware setup was similar to the preliminary configuration described in [9], with the addition of improved vibration isolation and the use of the foot bindings instead of foot straps. The BCG scale platform was mounted to a vibration-isolated metal plate on the aircraft's frame. Vibration isolation was accomplished using visco-elastic washers (Sorbothane®, Kent, OH) sized for a peak dampening frequency of 30 Hz, just above the frequency of the BCG measurement filters. The scale was then attached to this plate and preloaded with a stanchion crossbar. Test subjects were mechanically coupled to the scale by a pair of Lexa® snowboard boot bindings (Burton®, Burlington, Vermont). The scale-based BCG, accelerometry-based BCG, and ECG were recorded with custom data acquisition hardware and software. A LIS344ALH triaxial accelerometer (STMicroelectronics®, Genevia, Switzerland) was taped to the subject's center of mass for free-floating measurements comparable to previous research [11]. The two measurement configurations are shown in Fig. 2.

The BCG circuit consists of an analog amplifier and filter connected to the scale's strain gauge in a Wheatstone bridge configuration. Analog filtering was accomplished through a 4^{th} order Sallen-and-Key band-pass filter chain with a high- and low-pass cutoff of 0.01 and 100 Hz respectively, and a mid-band gain of 31 dB. The accelerometer signal conditioning circuit consisted of a filter chain with the same frequency characteristics. A DC-coupled accelerometer was used to define the microgravity segments of the flight during post-processing. The ECG was recorded with a custom circuit connected to gel electrodes in the Lead II (LL-RA) configuration. All signals were sampled at 256 Hz by the 12-bit ADC of a Shimmer® module (Shimmer Research, Dublin, Ireland), and recorded by an onboard laptop with custom MATLAB® (Mathworks®, Natick, MA) software.

B. *Parabolic Flight Dataset*

Six healthy males (ages 20-56, mean 38) and four healthy females (ages 19-40, mean 27) each participated in a series of 14-20 parabolic maneuvers, each lasting approximately 17 seconds, to record the scale-based and accelerometry-based free-floating BCG. Ground measurements of each subject were taken upon landing within an hour post-flight. An average of 148 scale-based microgravity heart beats, 48 scale-based ground beats, and 40 free-floating beats were measured for each subject.

C. *Signal Processing*

The microgravity portion of the recordings were first identified by examining the DC-coupled accelerometer magnitude. Then, in addition to the analog signal conditioning mentioned in Section II.A, several digital signal processing techniques were employed. First, the scale- and accelerometry-based BCG signals were digitally band-pass filtered to 1-20 Hz using an 80 dB/decade FIR filter. The baseline was then removed by subtracting a 0.5-second 3^{rd} order moving polynomial fit (Savitzky–Golay) of the filtered signal. The resulting beats were then ensemble averaged.

Ensemble averaging was done by aligning each beat of a subject's recording to the corresponding ECG R-wave peak in a matrix:

$$X[n] = \begin{bmatrix} x_1[n] \\ x_2[n] \\ \vdots \\ x_M[n] \end{bmatrix}, \quad n = 1, \ldots, L \tag{1}$$

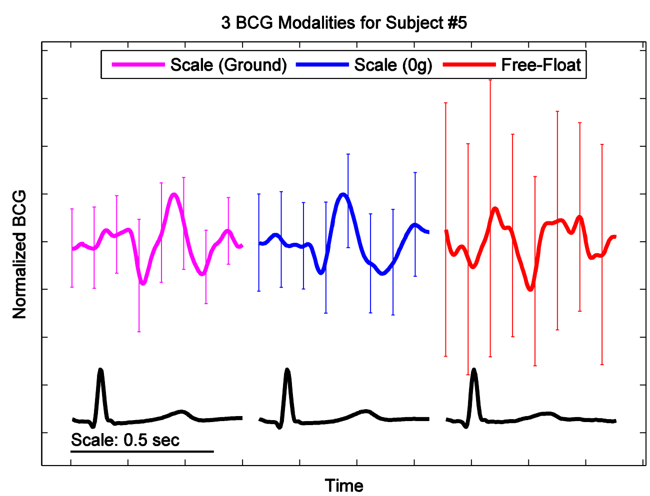

Fig. 3. Comparison of BCG measured by the scale device on the ground (top left) and in microgravity (top center), and via accelerometer while free-floating (top right). The ECG (bottom) R-wave peak was used to ensemble average each trace shown. Error bars show the standard deviation at each point. Normalization was performed on the waveforms to align each beat by subtracting its mean and equalizing the minimum/maximum peak.

where X is a subject's beat matrix, M is the number of beats, and L is the sample length of each beat. In this study, L=153 (0.6 seconds), where the R-wave peak is aligned at n=27 (0.1 seconds). The ensemble average of X is defined as:

$$EA(X)[n] = \frac{1}{M}\sum_{i=1}^{M} x_i[n], \quad n = 1, \dots, L \tag{2}$$

This ensemble averaged value is used to identify the J-wave peak in the BCG for RJ timing analysis as shown in Fig. 1. A comparison of ensemble averaged scale-based BCG beats on the ground and in microgravity, and accelerometry-based free-floating beats is shown in Fig. 3.

D. SNR Estimation

The SNR of each subject's BCG was estimated by calculating the average sample correlation coefficient SNR estimation between distinct pairs of sequential beats: $\{(x_1, x_2), (x_3, x_4), \dots, (x_{M-1}, x_M)\}$. This method, summarized below, provides an unbiased SNR estimation when there is a large number of pairs [14].

For each pair (x_j, x_k), the sample correlation coefficient, r, is defined as:

$$r = \frac{\frac{1}{L}\sum_{n=1}^{L}(x_j[n] - \overline{x_j})(x_k[n] - \overline{x_k})}{\sqrt{\frac{1}{L}\sum_{n=1}^{L}(x_j[n] - \overline{x_j})^2 \frac{1}{L}\sum_{n=1}^{L}(x_k[n] - \overline{x_k})^2}} \tag{3}$$

where $\overline{x}$ denotes the average value of vector x. The SNR estimate SNR_r is then defined as:

$$SNR_r = \mathrm{A}\frac{r}{1-r} + B \tag{4}$$

for constants A and B as given in [14]:

$$A = \exp\left(\frac{-2}{L-3}\right), \qquad \mathrm{B} = -\frac{1}{2}\left(1 - \exp\left(\frac{-2}{L-3}\right)\right) \tag{5}$$

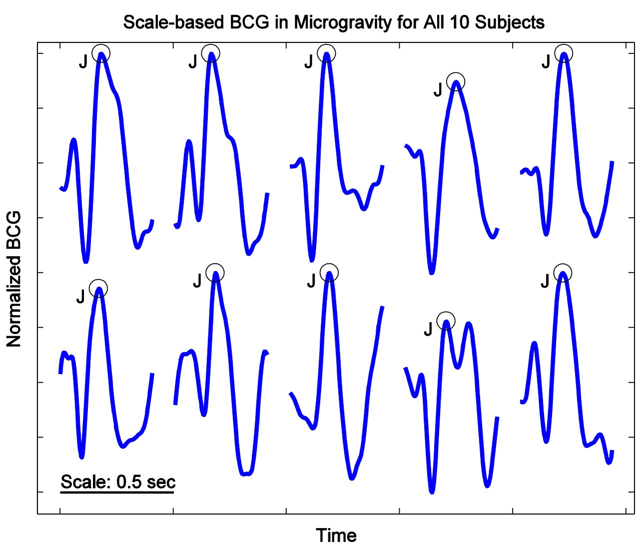

Fig. 4. Ensemble averaged scale-based microgravity BCG recordings from each subject (#1-10, ordered left to right then top to bottom). Each beat shown is 0.4 seconds, beginning at the ECG R-wave peak. For clarity, normalization was performed on the waveforms to align each beat by subtracting its mean and equalizing the minimum/maximum peak.

TABLE I. TIMING RESULTS: SCALE GROUND VS. MICROGRAVITY

	RJ Interval [ms]		
Subject ID	***Ground***	***Microgravity***	***Difference***
1	215	180	35
2	211	156	55
3	203	156	47
4	207	227	-20
5	258	195	63
6	203	168	35
7	219	180	39
8	211	172	39
9	250	180	70
10	215	191	23
Mean	219.11	180.43	38.68
S.Dev.	19.10	20.74	24.80
Coeff. of Var.	8.72%	11.49%	64.11%

Negative SNR_r values were set to zero before averaging. For SNR comparisons, only the first M beats in each dataset were included, where M is the smaller of the two dataset sizes.

III. RESULTS

The dataset was analyzed in terms of the RJ interval of each subject on the ground vs. microgravity, and the SNR of each subject's BCG waveform on the scale-based method vs. free-floating method. The BCG waveforms for each subject used to make these calculations are depicted in Fig. 4.

A. RJ Interval Timings

The RJ interval is defined as the time between corresponding ECG R-wave and BCG J-wave peaks. This is calculated on the ensemble average (2) of each subject's beat matrix (1). RJ interval timings for each subject are given in Table I. The right column shows the difference in this timing between ground and microgravity measurements. In 9 of 10 total subjects, this timing is decreased. The average decrease over the dataset was 38.68 ms (Std. Dev. = 24.80 ms). A single-tailed paired T-test showed that the difference between these two distributions is significant ($P < 0.001$).

B. SNR

The estimated SNR of scale-based and free-floating BCG in microgravity were compared using the sample correlation coefficient method (4). The estimated SNRs for each subject are given in Table II. All free-floating measurements were based on a single longitudinal y-axis as defined in [15]. The right column shows the difference between scale and accelerometry-based measurements. In 8 of 10 subjects, the SNR of the scale-based measurement was higher than that of the free-floating measurement. The average increase over the dataset was 2.08 (6.34 dB) with a standard deviation of 1.39. When compared to the three-dimensional free-floating BCG magnitude, the scale-based SNR was, on average, a factor of 5.44 (14.71 dB) higher with a standard deviation of 4.52.

IV. ANALYSIS AND DISCUSSION

The first key finding of this study was a consistent decrease in scale-based RJ interval after transitioning from a ground to microgravity environment (Table I). This observation was consistent in 9 of 10 subjects, and shown to be statistically significant by a T-test. No obvious demographic abnormality

TABLE II. SNR RESULTS: MICROGRAVIY SCALE VS. FREE-FLOATING

Subject ID	*M*	*SNR$_r$* Estimate *Scale*	*Free-Floating*	*Difference Factor*
1	34	0.69	0.32	2.13
2	16	0.60	0.21	2.86
3	56	0.99	0.92	1.08
4	72	1.02	0.26	3.91
5	66	0.92	0.20	4.50
6	28	0.36	0.68	0.53
7	18	0.22	0.76	0.29
8	26	0.42	0.36	1.15
9	60	0.71	0.29	2.44
10	22	0.65	0.35	1.87
Mean		0.66	0.44	2.08
S.Dev.		0.27	0.25	1.39
Coeff. of Var.		40.87%	58.04%	67.07%

was able explain the outlier. This change is likely due to the transient increase in venous return, and consequent decrease in pre-ejection period, experienced in microgravity. In the preliminary study [9], a single subject from a different dataset was observed to have a slight increase in RJ interval (9 ms), but not shown to be significant because of the sample size.

The scale-based BCG in microgravity yielded higher SNR versus the accelerometry-based free-floating methods in 8 of the 10 subjects tested. This dataset demonstrates the robustness of the scale-based approach for BCG monitoring, and poises it as a viable solution for hemodynamic monitoring of astronauts on extended missions where cardiovascular alterations may result. With a tethered scale-based system as described in this study, astronauts can simply maneuver to the scale platform, quickly latch their feet into the foot bindings, and be securely measured without constantly attempting to avoid free-floating collisions. This multi-g system can also be used in fractional-g environments such as the Moon or Mars.

The major limitation of a scale-based approach is its capability to only measure the BCG in the single longitudinal axis. The benefits of triaxial BCG allows for a more comprehensive assessment of BCG changes and other mechanical cardiac parameters such as maximal systolic force [10]. However, relevant hemodynamic information can still be obtained with a single-axis BCG recording [5-8].

With the feasibility of scale-based BCG recordings demonstrated in microgravity, and the RJ interval timing differences validated with multiple test subjects, future research is focused on modeling the timing difference phenomenon in order to quantitatively link microgravity measurements to those taken on the ground.

V. CONCLUSION

A scale-based BCG hemodynamic monitoring system was developed and tested for microgravity applications in a parabolic flight experiment. Results demonstrate that the signal quality of the scale-based BCG is higher than accelerometry-based free-floating BCG measured on the same subjects by an average factor of 2.08 (6.34 dB) in this dataset. Results also indicate there is an average decrease of 38.7 ms in RJ intervals after subjects transitioned from a ground to microgravity environment. The physical explanation of this phenomenon is motivation for future work.

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