Ballistocardiography for Monitoring Cardiovascular Deconditioning in Long-Duration Missions

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Abstract

The primary objective of this experiment is to demonstrate the use of a clinically-tested ballistocardiograph (BCG) hemodynamic monitoring scale in microgravity, and demonstrate its utility for space applications by establishing the correlation between ground-based and microgravity measurements. Clinical studies conducted at Stanford have demonstrated that this BCG scale hardware is useful for monitoring cardiac output and stroke volume change, contractility change, cardiac resynchronization therapy, arterial stiffening, and monitoring of central pressures. All of these measurements can be useful to detect well-known cardiovascular physiology changes in weightless environments, where astronauts often return to Earth with microgravity-induced deconditioning. As a second objective, we aim to measure the whole-body acceleration BCG (while standing) to further link these two measurement modalities and provide a means to compare previously published free-floating acceleration BCG to scale-based BCG and terrestrial data. The results shown validate our primary objective, and interesting physiological differences induced by microgravity are evident in the reduced RJ-interval of all subjects in the dataset.

Introduction

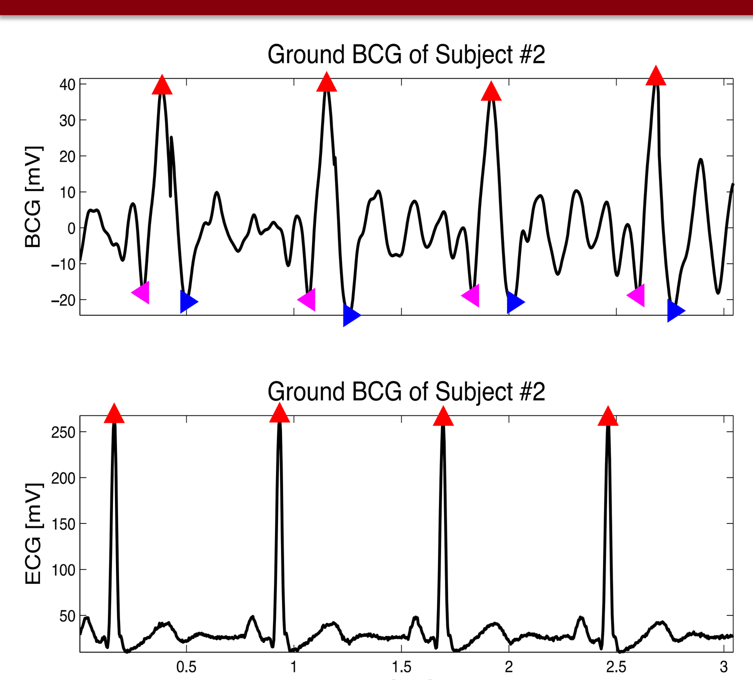


Figure 1. BCG can be obtained by standing still on a sensitive weight scale (top). Various useful physiological parameters can be derived from the timing differences between the simultaneously recorded ECG (bottom), R peaks (red triangles), and the IJK complex of the trailing BCG waveform marked by the magenta (I), red (J), and blue (K) triangles.

The BCG is a non-invasive method of hemodynamic monitoring that measures the force due to the ejection of blood by the heart with each heartbeat. We successfully measure this using a sensor platform consisting of a typical bathroom scale modified to include filtering and amplification electronics. When a subject's feet are tightly mounted to the scale with boot bindings, the small force caused by each heartbeat can be sensed as shown in Figure 1. Although this scale-based BCG is our primary objective, we also successfully measure the BCG of free-floating subjects using a sensitive accelerometer mounted to the body. Our experiment setup consists of the modified scale and a custom wearable wireless monitor that conditions the accelerometer-based BCG signal and records the electrical activity of the subject's heart by electrocardiogram (ECG). Simultaneous measurement of the ECG and BCG allows us to validate the BCG with the known heartbeat timings in the ECG signal.

Zero-G Data Collection

The BCG of 10 subjects was recorded in microgravity over 4 parabolic flights (128 parabolas). Scale-based and accelerometer-based measurements were taken while standing coupled to the scale, and free-floating measurements were taken while floating in the cabin.

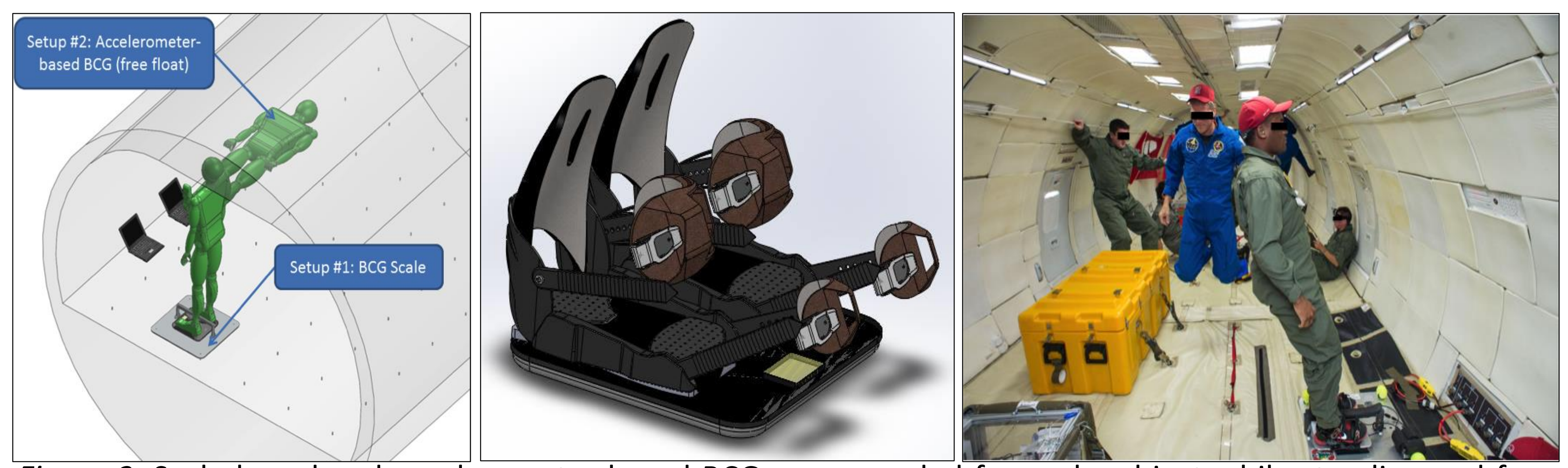


Figure 2. Scale-based and accelerometer-based BCG was recorded for each subject while standing and free-floating (left). Each subject was mechanically coupled to the scale with boot bindings (center), allowing them to be measured without floating away during the parabola (right, test subject standing on right).

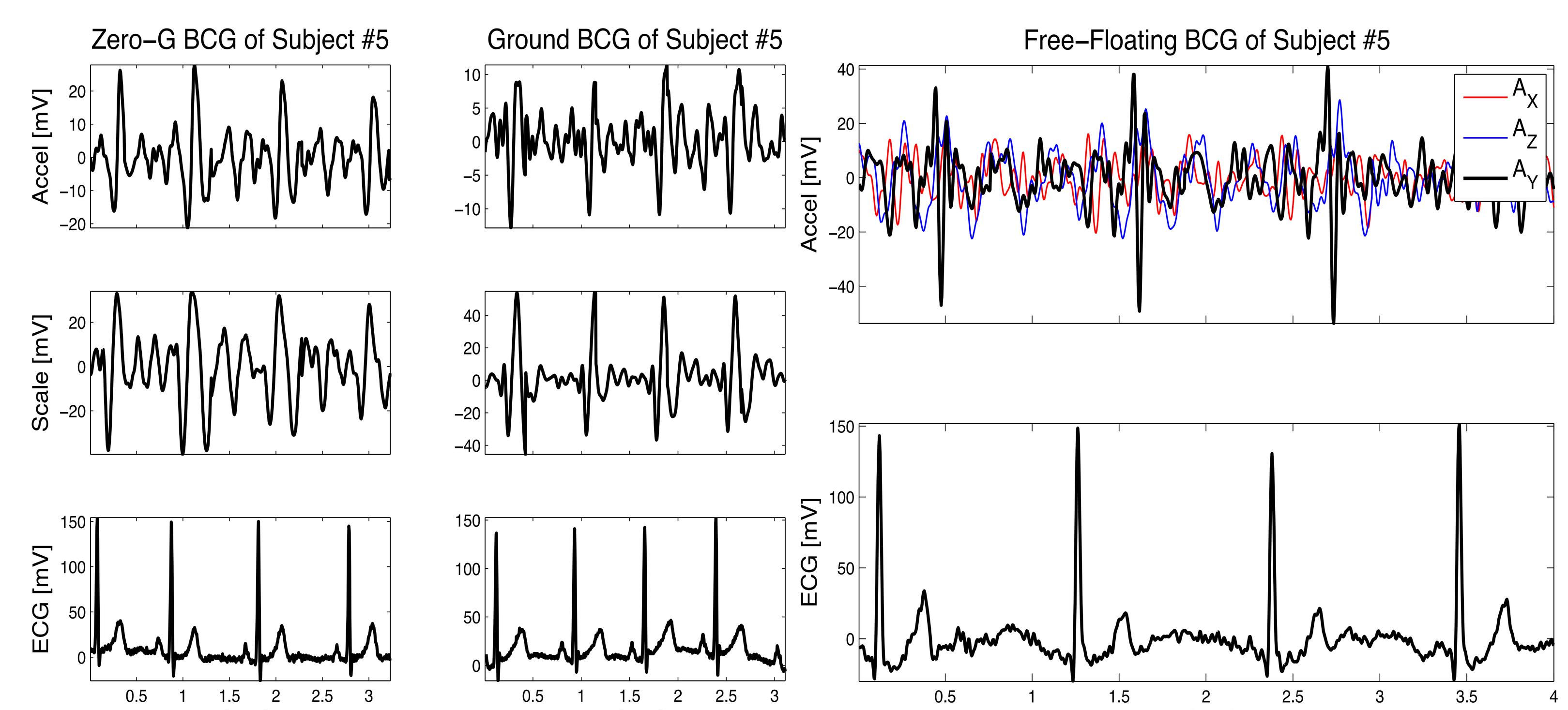
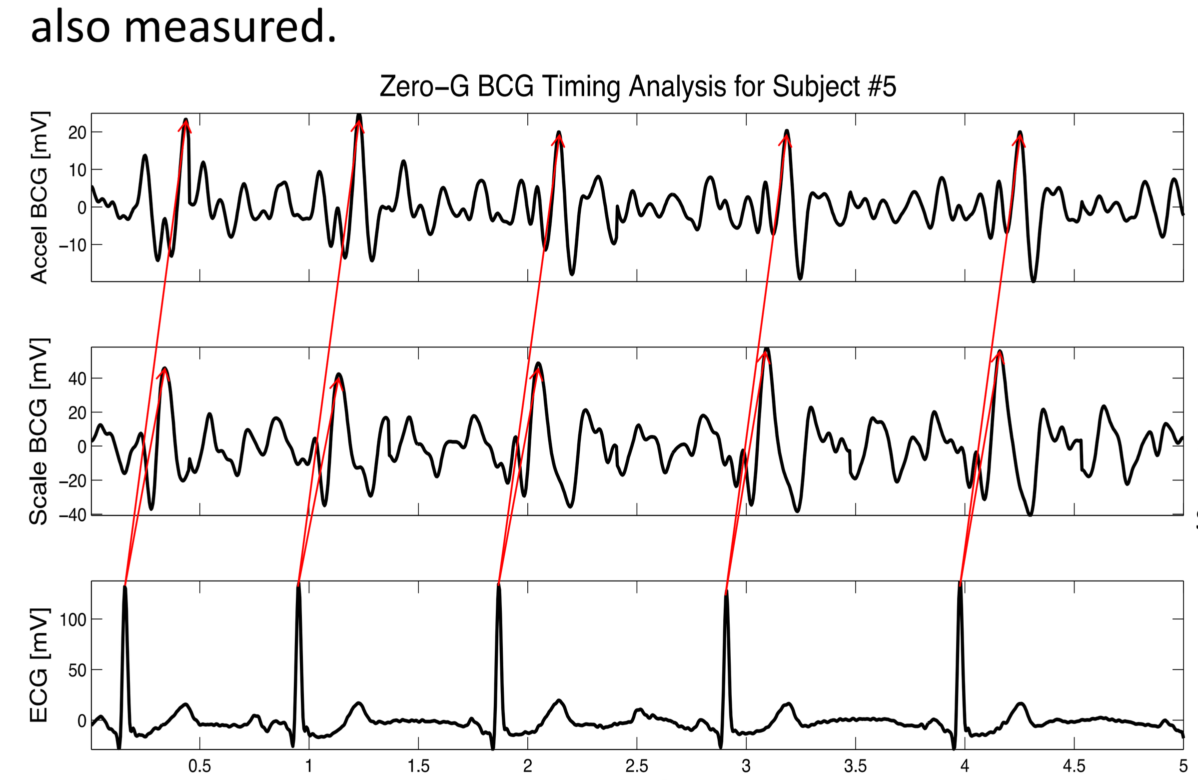


Figure 3. Ensemble averaged BCG recordings from Subject #5 while standing on the scale in microgravity (left), terrestrial gravity (center), and while free-floating in microgravity (right).

Timing Analysis

The RJ-interval is the timing between the ECG R-wave peak and the J-wave peak in the BCG as described in Figure 1. The RJ-interval on a scale-based BCG was characterized extensively in clinical settings by our team, and is consistent with the timings measured in these microgravity experiments. Accelerometer-based BCG timings for scale and free-floating configurations were also measured.



Configuration (Subject #5)	Accel RJ-Interval	Scale RJ-Interval
Ground Scale	257 ms	248 ms
Zero-G Scale	275 ms	183 ms
Zero-G Free-Float	318 ms	n/a

Table 1. RJ-interval calculations from the small segment of Subject #5 data.

Figure 4. Red arrows show how RJ-intervals are calculated for scale-based and accelerometer-based BCG signals in microgravity.

Results

A robust system for measuring scale-based and accelerometer-based BCG in microgravity was successfully validated by comparing measurements taken during parabolic flight maneuvers with those taken on the ground immediately after the flight. The RJ-interval timings were then calculated from the data in both environments by measuring the time difference between the R-wave peak and the beat-to-beat ensemble average of the scale data synchronized to each corresponding R-wave. Notably, the scale-based interval timings are significantly reduced for all subjects when in microgravity as shown in Table 2, while the accelerometer-based timings remained roughly constant.

Table 2. Scale-based BCG RJ-interval calculations from 6 of the 10 subjects. In all cases, the RJ-interval is significantly reduced in microgravity vs. the terrestrial measurement. The data from the remaining 4 subjects is currently being processed.

ID	Ground R-Interval	Zero-G RJ-Interval
1	215 ms	180 ms
2	211 ms	156 ms
3	203 ms	156 ms
4	219 ms	180 ms
5	258 ms	195 ms
6	203 ms	168 ms

Discussion

We successfully validated this system for accurately measuring the BCG of human subjects in a reduced gravity environment, which can be used to monitor cardiac deconditioning of astronauts on long-duration missions. The flat form factor of the scale device allows it to be mounted on the floor or wall of a small spacecraft such as the proposed NASA Orion capsule, enabling easy BCG measurement that is not possible with previously published free-floating accelerometer-based methods because of the cramped environment. Upon completion of this flight campaign, a technology readiness level (TRL) of 6 was achieved.

Quantitative timing analysis of the RJ-interval of the scale-based measurements reveals a physiological change induced by microgravity that can be seen in significantly reduced intervals for all test subjects. The modeling of this as-yet unexplained phenomena is the focus of our current research.

Acknowledgements

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