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Potential of Weight Scale Based Ballistocardiography for Identifying Orthostatic Intolerance: A Tilt Table Study

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ABSTRACT

Autonomic cardiovascular control is critical in regulating blood pressure during postural transition, failure of which could lead to dizziness and fall (orthostatic intolerance). In this study, the feasibility of Ballistocardiography (BCG) for quantifying autonomic nervous system activity in relation to gold standard electrocardiogram (ECG) was tested.

Simultaneous ECG, blood pressure, photoplethysmography (PPG), and BCG were continuously acquired during 5-minutes of stand tests (before and after tilt test up to 60°) from 10 participants. Heart period was derived from ECG and BCG represented as RR and JJ intervals, respectively. Spectral analysis of heart period (both RR and JJ) was performed by calculating power distributed in low-frequency (0.04-0.15 Hz) and high-frequency (0.15-0.4 Hz) bands. Strong correlation ($r>0.87$ for Pre-tilt and $r>0.97$ for Post-tilt, $p<0.001$) between ECG and BCG derived LF, HF, and LF/HF was observed, except for LF/HF($r>0.63$ for Pre-tilt). The Wilcoxon rank sum test revealed no difference ($p>0.10$) in BCG or ECG LF, HF, and LF/HF during the two stand tests.

The findings of the study highlighted the feasibility of monitoring cardiovascular control via weight-scale BCG. Therefore, the developed system can gain utility as a portable and cost-effective system for early detection and mitigation of falls associated with autonomic dysfunction.

1. INTRODUCTION

Falls due to failure to maintain blood pressure (orthostatic intolerance) during standing is common in elderly and people with neurological disorders and is associated with reduced quality of life in such groups [1]–[3]. Baroreflex mediated cardiovascular control i.e. increase in sympathetic activity (causing elevation in heart rate and systemic vascular resistance) is critical in regulating blood pressure during standing [4], [5]. Frequency domain analysis of heart rate variability (HRV) derived from ECG is a recognized technique for non-invasive assessment of sympathetic and parasympathetic activity [6]–[8]. However, the requirement of electrode placement limits portable application of ECG for assessment of autonomic cardiovascular control.

Ballistocardiography (BCG) is a measurement of reaction forces resulting from cardiac ejection to the aorta. BCG research within the last two decades has shown promise in both long term, such as longitudinal monitoring of cardiovascular health [9], and short term monitoring, by analyzing trends during exercise recovery [10]. Weight scales have the advantage of being inexpensive and easily modified for multisignal physiological monitoring [11]. As such, they are ideal platforms for prototyping BCG acquisition systems.

In this study, the feasibility of monitoring autonomic activity via BCG by comparing its performance with gold standard ECG was tested. Previous studies have induced a change in cardiovascular activity by changing position from supine to standing [12] or requiring physical activity from the participant. To measure the ability of BCG to provide actionable data pertaining to orthostatic intolerance, head-up tilt was utilized. This allowed for further challenge of the cardiovascular system. Additionally, the abrupt change from 60° tilt to standing position induced sway in the participants, activating leg muscles for pumping venous blood back to the heart [13], providing a superior environment for testing BCG's relation to orthostatic intolerance.

By assessing fluctuations in RR or JJ intervals HRV can be derived (Figure 1). HRV is a measure of the variation between heartbeats and can provide important, predictive cardiovascular information [8]. ECG is the preferred method for obtaining HRV due to its robust signal and direct correlation to cardiovascular activity. BCG, however, may present an alternative, especially for long term in-home monitoring, to ECG [14]. Although much less robust to motion artifacts, BCG allows for easier acquisition

through cheaper means than ECG by neglecting the need for body-contact electrodes and elaborate connections. Using a commercially available bathroom weight scale and its corner-fitted strain gauges, it is possible to acquire a BCG signal using only a simple interfacing circuit [11].

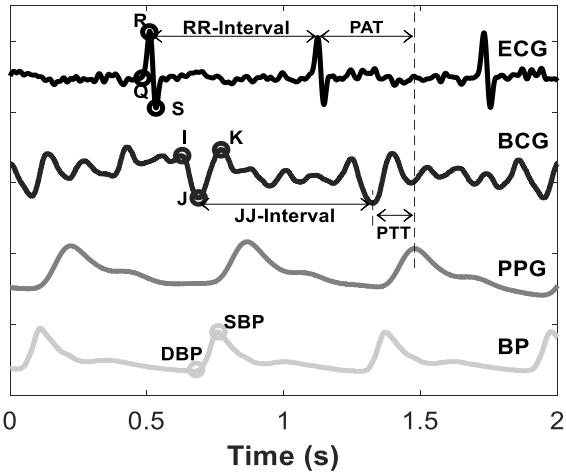

Figure 1. An example of simultaneous recording of ECG, BCG, PPG, and BP signals. IJK complex of BCG signal and QRS complex of ECG signal denoted.

2.METHODS

2.1. Signal Acquisition

Ten volunteers were studied under a protocol approved by the University of North Dakota Institutional Review Board upon providing written consent. The participants were young and without any current health issues (age: 25.6 ± 3.5 years; gender: 8 males, 2 females; height: 178 ± 7 cm; weight: 71.2 ± 9.5 kg). Each participant was fitted with three gel electrodes to produce ECG. One on each forearm as well as a reference ground on the back of the right hand. PPG was acquired from participants right index finger. Beat-by-beat finger blood pressure (Finapres Nova, FMS, The Netherlands) was acquired by placing a plethysmography cuff on the participant's middle finger (left hand) who was asked to keep their hand at heart level for the duration. BCG was acquired through a customized Tanita BC-534 weight scale by using an interfacing circuit based on a design by Inan et. al. [15] between the weight scale load cells and the acquisition system. This circuit incorporates analog band-pass filtering between 0.1 and 25 Hz which is the minimum cutoff frequency for retaining accuracy in BCG time interval detection [16]. All the signals were recorded on a laptop computer through an MP160 BIOPAC modular data acquisition system (BIOPAC Inc, Goleta, CA) with a sampling rate of 2000 Hz.

Data was recorded over six different subprotocols, each lasting five minutes. To ensure minimal interference with the signals, the lights were dimmed, and the area was cleared of any non-research personnel. For baseline recordings the participant was asked to lay supine on a tilt table. Then, they stood on a weight scale. They were asked to stand still and breathe normally. To induce a change in blood pressure the next three five-minute segments consisted of the participant being secured to the tilt table and tilted, head up, in 20° increments. After five minutes tilted at 60°, the participant was released directly onto the weight scale from the tilt table in order to minimize muscle contraction in the legs as it would affect BP. The participant then stood on a weight scale for five minutes. As this last segment carried an increased risk of the participants falling or losing consciousness, three researchers were stationed around them in a manner that would allow for catching them should they fall.

2.2. Signal Processing

A custom MATLAB program was developed specifically for peak detection and parameter extraction of the acquired signals. Since PPG provided the most consistently clean signal, the PPG peaks were used as a fiducial mark for any subsequent peak detections. Preliminary detection of R waves, using a wavelet transform of the ECG signal, was performed. These peaks were used in conjunction with the PPG peaks to define an expected R wave position. A Gaussian distribution template with a mean at the expected R wave value was multiplied with the ECG signal over each PPG interval, resulting in improved R wave prominence. This same method was applied to find the J wave from the BCG signal using the R waves and the PPG peaks as reference. Using this program, the RR and JJ intervals were calculated (Figure 2). Both the diastolic BP (DBP) and the systolic BP (SBP) were detected in the blood pressure waveform to determine beat-to-beat blood pressure metrics.

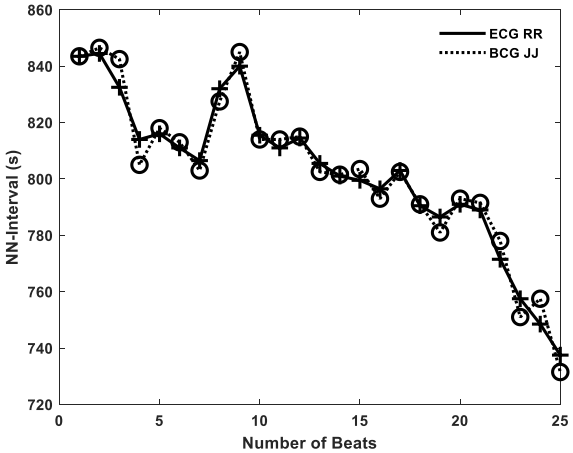

Figure 2. Interval Comparison between ECG RR intervals and BCG JJ intervals over 25 consecutive heartbeats.

Standard guidelines for HRV frequency domain analysis [8] recommends the following statistical measures: HF, LF, and LF/HF. For these metrics NN intervals were used instead of RR and JJ intervals, henceforth denoted RR_N and JJ_N, respectively. That is, all non-abnormal intervals. Abnormal intervals (RR_A) were defined as:

$$\overline{RR} + 5\sqrt{\frac{\sum_{i=1}^{N}(RR_i - \overline{RR})^2}{N-1}} < RR_A < \overline{RR} - 5\sqrt{\frac{\sum_{i=1}^{N}(RR_i - \overline{RR})^2}{N-1}}$$

for RR intervals and similarly for JJ intervals. For HF and LF calculations, the tachogram for each interval was interpolated using cubic spline interpolation and subsequently resampled at a sampling rate of 2 Hz. Using Welch's power spectral density estimate with a Hamming window produced a power density spectrum (PDS) used to estimate the power of the LF and HF bands.

3.RESULTS

The mean SBP for the participants were 141 ± 24 and 146 ± 24 mmHg for pre and post tilt, respectively. For DBP the values were 80 ± 16 and 84 ± 18 mmHg. Using the Wilcoxon rank sum test no significant change in participant SBP from pre to post tilt ($p > 0.10$) was found, but a significant change in DBP ($p < 0.10$) was observed. The mean arterial blood pressure (MABP) showed pre and post tilt values of 100 ± 18 and 105 ± 20 mmHg, respectively. HR values for pre-tilt were 84 ± 7 and 87 ± 10 bpm for post tilt. HR showed no significant change ($p > 0.10$).

The PDS allowed for the extraction of the LF and HF power for ECG and BCG for each of the six individual participants. These values were 0.57 ± 0.13, 0.42 ± 0.13 (ECG) and 0.57 ± 0.15, 0.42 ± 0.15 (BCG) for the pre-tilt data. For the post tilt data LF and HF were 0.69 ± 0.15, 0.30 ± 0.15 (ECG) and 0.67 ± 0.17, 0.32 ± 0.17 (BCG) all in normalized units. This result is summarized in Figure 3 along with the HR. Calculating the p-value based on these findings by comparing BCG to ECG yielded: 0.99, 0.99, and 0.99 for LF, HF, and LF/HF respectively based on pre tilt data and 0.99, 0.99, and 0.90 for post tilt. All these values suggest a strong correlation between BCG and ECG which is reflected in the correlation coefficients found for each frequency parameter. For pre tilt, BCG and ECG showed a correlation coefficient of $r>0.87$, $r>0.87$, and $r>0.63$ for LF, HF, and LF/HF, respectively. Post tilt data produced $r>0.97$, $r>0.97$, and $r>0.97$ for LF, HF, and LF/HF, respectively**.** LF, HF and LF/HF showed a mean and STD difference between ECG and BCG of 0.046 ± 0.056, 0.046 ± 0.056, and 0.434 ± 0.682, respectively, for pre tilt and 0.031 ± 0.027, 0.031 ± 0.027, and 0.393 ± 0.31 for post tilt, all in normalized units.

4.DISCUSSION

Early detection of orthostatic intolerance is currently lacking a non-invasive and portable solution. The goal of this study was to show that BCG can be used as an adequate substitute for ECG in the interest of longitudinal tracking of cardiovascular control, thus providing a method for non-invasive, low-effort orthostatic intolerance detection. During orthostatic challenge induced by pre and post tilt standing, the feasibility of BCG for monitoring autonomic cardiovascular control was studied. The results show strong agreement between ECG and BCG with regards to HRV parameters during both and pre and post tilt standing.

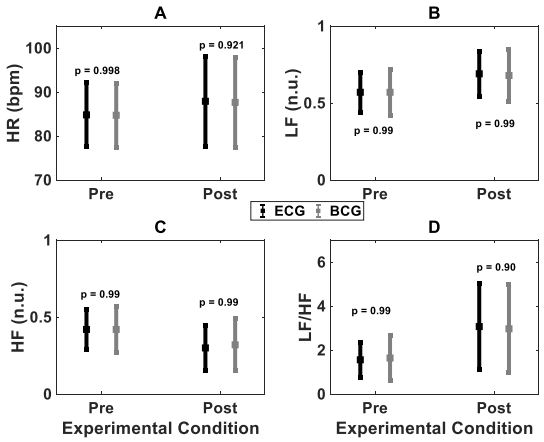

Figure 3. Mean ± STD of LF and HF power in normalized units derived from ECG and BCG during pre and post tilt standing. No difference ($p>0.10$) was observed between ECG and BCG derived HRV features.

HR derived from BCG was observed to be strongly correlated ($r>0.99$) with ECG derived HR. Further, no difference between ECG and BCG derived HR was observed under the two experimental conditions (Figure 3-A). The frequency domain parameters showed a strong correlation between the signals, this observation supports the hypothesis of monitoring sympathetic, vagal, as well as sympathovagal balance, a key indicator of baroreflex function, via BCG.

The strong correlation between ECG and BCG derived HRV frequency shows the potential of a weight scale based BCG system to produce accurate information on orthostatic intolerance. Even if the participant displays low amplitude BCG, which can happen due to several factors not necessarily related to cardiovascular health, the important segment of increased cardiovascular activity will naturally be more suited for BCG. This is because the increased sympathetic nerve activity will reduce the effect of motion artifacts in relation to the reactive force generated by aortic ejection of blood.

5.CONCLUSION AND FUTURE WORK

The frequency domain HRV features derived from BCG were significantly correlated ($p<0.001$) with the ones derived from ECG. Furthermore, no difference ($p>0.10$) between the ECG and BCG derived features were observed. This finding supports the feasibility of monitoring autonomic cardiovascular control in a portable fashion via weight scale BCG. By comparing individual measurements over time with the user as a baseline, BCG can be used for early detection of abnormal changes in cardiovascular control which assist in early identification and prevention of falls due to orthostatic intolerance.The major limitation of the present study was the limited sample size. Accordingly, a future study in a bigger cohort is warranted to demonstrate the utility of BCG developed system for monitoring cardiovascular control. Further, the effect of sex on BCG should be investigated to ascertain its population-wide application. Moreover, in addition

to HRV indices, in future, blood pressure can be estimated utilizing the concept of pulse transit time (PTT), for such purposes BCG can be employed for proximal timing while PPG can be used for timing the distal pulse (Figure 1). The ability to simultaneously acquire heart rate and blood pressure will provide an opportunity to assess heart rate and blood pressure interaction, a vital control mechanism, which ascertains cardiovascular homeostasis [17].

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