A Novel Wearable Insole BCG as a Surrogate of the Standard Vertical Weighing Scale BCG

José A. García-Limón [1, 2], Carlos Alvarado-Serrano [2], Ramon Casanella [1]

[1] Instrumentation, Sensors and Interfaces Group, Universitat Politècnica de Catalunya - Barcelona Tech, Castelldefels, Barcelona, Spain.

[2] Bioelectronics Section, Department of Electrical Engineering, Cinvestav, Mexico City, Mexico

Abstract

This work presents a new wearable system based on a piezoelectric sensor embedded in a shoe insole to obtain the ballistocardiogram (BCG). The vertical BCG can be related to relevant cardiovascular parameters such as aortic Pulse Transit Time (a-PTT) and potentially, blood pressure (BP), but, as different mechanical interfaces and measurement axes can significantly change the BCG waveform, the BCG waveform shape and peak timings of the new wearable BCG system need to be compared with the well-known standard vertical BCG obtained on a weighing scale, to determine its potential to track relevant cardiovascular parameters from it. For the study, BCG and ECG were recorded from 7 healthy subjects obtained on a scale and in the insole system in both standing and sitting positions. The results obtained show that weighing scale BCG and the insole BCG obtained while standing present a very similar shape (and very different from the one obtained while seated) and the difference between the main peak time positions obtained with the two systems in most cases is less than the characteristic uncertainty of these measurements and therefore, that the new system has the potential to obtain the same cardiovascular parameters but with the added advantage of the much more continuous tracking capabilities of wearable systems.

1. Introduction

Recently, there has been growing interest in the development of devices to monitor cardiovascular health status in nonclinical settings. These devices should be noninvasive, easy to use, and should interfere as little as possible with the daily lives of their users. One measure with great potential in this regard, and one that has attracted increasing interest in recent years, is the ballistocardiogram (BCG), a mechanical signal originating from whole-body recoil forces in reaction to cardiac ejection of blood through the vascular tree [1]. The advantage of BCG systems over other alternatives is that measurements can be made by placing sensors, such as strain gauges, load cells or piezoelectric sensors, among others, on everyday objects, such as the back of a chair [2], a bed [3] or a modified bathroom scale [4].

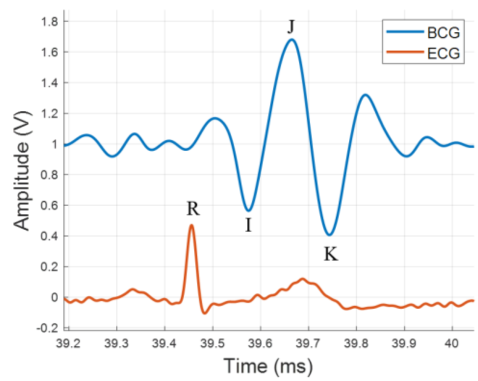

Figure 1. Typical BCG and ECG waveforms with the letters used to designate the main waves of interest.

Furthermore, recent research in this field has shown that the waveform of BCG measured in a vertical position is due to blood pressure gradients in the ascending and descending aorta [5], demonstrating its potential as a signal for the diagnosis and monitoring of cardiovascular health. In this sense, it has also been found that the main peaks of the signal, called I, J and K (see fig.1) are potentially related to cardiovascular parameters of interest. Thus, it has been shown that BCG peak I can be used as a proximal time reference for the measurement of pulse transit time (PTT), pulse wave velocity (PWV) and, therefore, has the potential for cuff-free blood pressure monitoring [6]. On the other hand, preliminary studies have also suggested that the J-peak could be used as a surrogate for distal time, whereby the IJ interval can be correlated with aortic PTT (a-PTT) [7].

However, one of the main difficulties in obtaining useful cardiovascular information from BCG is that the shape and times of the signal peaks can be modified by the mechanical interfaces of the systems in which the measurement is implemented. This effect is in general particularly relevant in the new BCG wearable systems, where various types of mechanical sensors are placed on the body [8]-[9] in order to continuously measure BCG. In them, the signal needs to be transformed through complex mechanical models of the whole-body structure in order to retrieve the standard vertical BCG measured with scales, which significantly complicates the applicability of this type of systems [10].

In this work, we present a new wearable system, in this case, based on a piezoelectric sensor incorporated in a shoe insole to measure vertical BCG. In the developed system, unlike previous approaches that placed this type of sensor in other positions that did not allow obtaining the BCG for subjects standing at rest [11], we propose the placement of the sensor in the heel area of a shoe insole with the hypothesis that in this area the weight of the subject is directly received and, therefore, it is possible to directly measure the impact of the longitudinal forces causing the BCG. In order to determine to what extent this new BCG can be used as a surrogate of the standard vertical BCG, the procedure and the results obtained from the comparison of the new sole BCG with the traditional vertical BCG obtained with a scale are shown in the next sections.

2. Material and methods

2.1 BCG insole acquisition system

To implement a BCG system in an insole, a piezoelectric sensor (DT4-028K Measurement Specialties, Inc.) with a thickness of 0.5 mm was used. This sensor was conditioned using a charge amplifier that acted as a high-pass filter, with a low cut-off frequency of 0.5 Hz together with a first-order active high-pass filter with a cut-off frequency of 0.5 Hz. In addition, a third-order active low-pass filter with a Butterworth response and a high cutoff frequency of 20 Hz was applied to define the bandwidth.

The sensor was placed on a generic insole in the heel support area, positioned on the floor to directly measure weight variations caused by BCG forces, as shown in Figure 2. As a reference, an ECG lead I using dry electrodes was used. The signal was filtered between 0.5 Hz (first order) and 40 Hz (first order) and amplified by 1000.

2.1 Weighing Scale BCG acquisition system

To validate the signals obtained from the insole system, the BCG signal was also obtained from four strain gauges of a bathroom scale connected in a Wheatstone bridge. To delimit the bandwidth, the signal was bandpass filtered (first order) between 0.5 Hz and 25 Hz and amplified by 15,000. As a reference we use the same ECG lead of the BCG insole acquisition system.

Both measurement systems were connected to a USB-7202 data acquisition system (Measurement Computing inc. ®) in which a sampling rate of 200 Hz was used. The acquired data were sent to the PC for display and storage using a graphical interface in LabVIEW®.

Fig 2. Sensor on shoe insole.

2.1 Experimental setup

BCG and the ECG were recorded from 7 healthy subjects (see Table 1), which gave their informed consent, for 2 minutes on the weighing scale in standing position and 2 minutes on the insole in standing and sitting position sequentially.

Table 1. Cohort characteristics

Subject	Gender	Age	Weight (kg)	Height (cm)
S1	M	28	80	177
S2	M	23	85	188
S3	M	31	76	170
S4	M	57	75	173
S5	M	38	95	175
S6	F	51	60	163
S7	M	43	115	173

In order to compare the BCG signals, thirty ensemble averages were obtained by applying Woody's method [12] selecting 20 random beats from each recording with the R wave of the ECG as a reference. Then, a final average was calculated to assess the similarity between the insole and scale systems. A quantitative comparison was performed between the positions of BCG fiducial points in the insole when standing and those in the weighing scale, with a particular focus on the IJK complex. The final Woody's averages were used as a reference for a more robust peak detection. Finally, a statistical analysis was performed by calculating the average positions of the IJK complex waves with respect to the ECG's R wave and the difference between the mean values obtained for each main peak in the two systems. The uncertainty of this difference was obtained by combining the standard deviations in the positions of each pair of peaks compared.

3. Results and discussion

The results of the final averages of three representative subjects are shown in Figures 3 to 5. It can be seen that the BCG waveforms of the scale and the insole in the standing position show significant similarity, although in some cases there is a slight delay in the peaks of the IJK complex. It should be noted that the insole lacks a structure similar to that of the scale to center the weight on the piezoelectric sensor, so a greater presence of motion artifacts is to be expected which, in addition to the intrinsic variability of the measurement in successive beats, may account for some of the slightly larger differences observed in some recordings.

Regarding insole BCG in seated position, it is evident that mechanical surface plays an important role in distorting the BCG signal. However, as can be observed in all subjects, a peak of significant amplitude prevails over the other waves, so this signal can be useful for robustly measuring heart rate on the sole of the foot when subjects are seated.

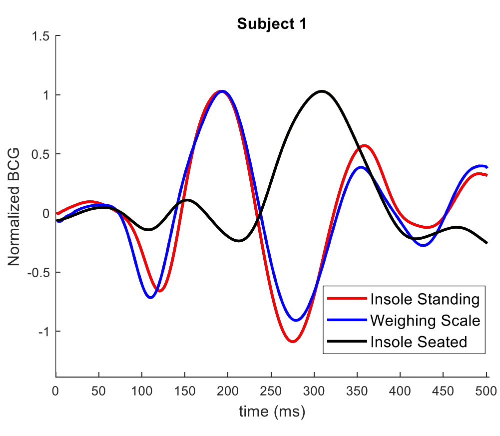

Figure 3. Final ensemble averages for the three measurements of subject 1.

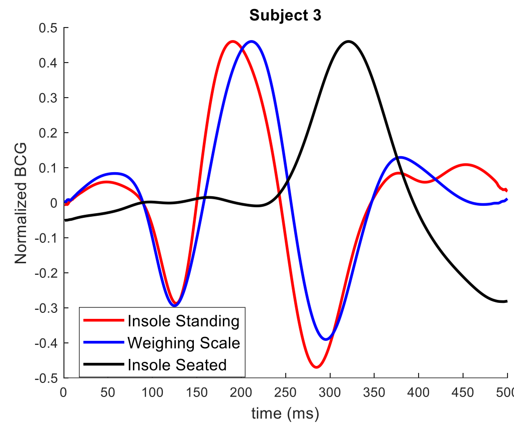

Figure 4. Final ensemble averages for the three measurements of subject 4.

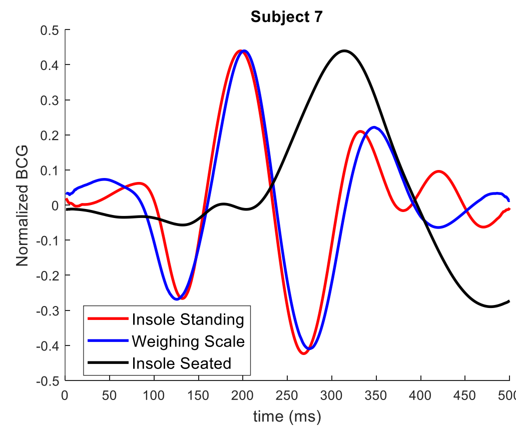

Figure 5. Final ensemble averages for the three measurements of subject 7.

Table 2 shows the mean values of R-I intervals obtained with the weighing scale and the insole in standing position and their differences for all subjects, that are consistently smaller than the uncertainty in all cases. For the R-J interval (Table 3) the difference between the averages slightly exceeds the uncertainty level only in one case (S3), and, finally, for the R-K interval (Table 4) in all records, the difference between the averages is lower than the uncertainty.

Table 2. Comparison of the R-I intervals between the weighing scale BCG and the insole standing BCG.

Subject/ Parameter	Mean R-I_{IS} (ms)	Mean R-I_{WS} (ms)	Difference (ms)	Uncertainty (ms)
S1	118.8	107.5	11.2	13.1
S2	140.4	132.5	7.92	14.6
S3	124.4	121.2	3.1	10.5
S4	123.3	116.4	6.9	13.1
S5	145.5	138.4	7.1	13.3
S6	119.7	119.6	0.1	26.2
S7	130.6	122.0	8.6	15.0

Table 3. Comparison of the R-J intervals between the weighing scale BCG and the insole standing BCG.

Subject/ Parameter	Mean $R\text{-}J_{IS}$ (ms)	Mean $R\text{-}J_{WS}$ (ms)	Difference (ms)	Uncertainty (ms)
S1	189.3	191.6	2.2	13.8
S2	217.3	221.9	4.6	15.7
S3	184.4	209.4	24.9	15.2
S4	197.6	204.9	7.3	14.3
S5	225.4	236.3	10.9	15.3
S6	196.8	207.5	10.6	17.4
S7	195.8	199.5	3.6	14.5

Table 4. Comparison of the R-K intervals between the weighing scale BCG and the insole standing BCG.

Subject/ Parameter	Mean $R\text{-}K_{IS}$ (ms)	Mean $R\text{-}K_{WS}$ (ms)	Difference (ms)	Uncertainty (ms)
S1	272.5	276.8	4.3	13.1
S2	301.3	317.2	15.8	13.2
S3	283.4	294.1	10.7	15.3
S4	275.8	277.9	2.1	14.5
S5	330.6	325.4	5.2	17.3
S6	289.8	270.8	19.0	20.1
S7	265.1	271.7	6.5	17.5

4. Conclusions

The results obtained from the comparison between the BCG from the scale and the BCG from the insole of the wearable system, measured while standing upright, show very similar shape and peak times. Therefore, the BCG obtained with the new system seems to have the potential to be used as a surrogate of the standard BCG to obtain the same cardiovascular parameters, without the need to use complex mechanical models to convert one signal into the other, and with the added advantage of the much more continuous monitoring capabilities associated with wearable systems.

Acknowledgements

This work was supported in part by the Spanish Agencia Estatal de Investigación under grant PID2020-116011RB-C21 (MCIN / AEI /10.13039/ 501100011033). The authors extend their gratitude to CONACyT for the financial support and fellowship provided to José Alberto García-Limón.

References

[1] O. T. Inan, P. F. Migeotte, K.-S. Park, M. Etemadi, K. Tavakolian, et al. Ballistocardiography and Seismocardiography: A Review of Recent Advances. Biomed. Heal. Informatics, IEEE J. 2015; 19(4): 1414–27.

[2] P. S. Luna and R. Pallàs, "Automatic Concealed Heart Rate Detection from the BCG in Seated Position," *IEEE Latin America Transactions*, vol. 13, no. 3, pp. 583–588, Mar. 2015, doi: 10.1109/TLA.2015.7069078.

[3] C. Carlson, V. R. Turpin, A. Suliman, C. Ade, S. Warren, and D. E. Thompson, "Bed-Based Ballistocardiography: Dataset and Ability to Track Cardiovascular Parameters," *Sensors (Basel)*, vol. 21, no. 1, pp. 1–13, Jan. 2021, doi: 10.3390/S21010156.

[4] R. Pallas-Areny, R. Gonzalez-Landaeta, O. Casas. Heart Rate Detection from an Electronic Weighing Scale. Physiol. Meas. 2008; 29(8): 979–88.

[5] C. S. Kim *et al.*, "Ballistocardiogram: Mechanism and Potential for Unobtrusive Cardiovascular Health Monitoring," *Scientific Reports 2016 6:1*, vol. 6, no. 1, pp. 1–6, Aug. 2016, doi: 10.1038/srep31297.

[6] C.-S. Kim, A. M. Carek, R. Mukkamala, O. T. Inan, and J.-O. Hahn, "Ballistocardiogram as Proximal Timing Reference for Pulse Transit Time Measurement: Potential for Cuffless Blood Pressure Monitoring," *IEEE Trans Biomed Eng*, vol. 62, no. 11, p. 2657, Nov. 2015, doi: 10.1109/TBME.2015.2440291.

[7] J. Gomez-Clapers, R. Casanella, and R. Pallas-Areny, "Direct Pulse Transit Time Measurement from an Electronic Weighing Scale," in *2016 Computing in Cardiology Conference (CinC)*, Vancouver, BC, Canada, Sep. 2016, pp. 773–776. doi: 10.22489/CinC.2016.223-364.

[8] D. Da He, E. S. Winokur, and C. G. Sodini, "An ear-worn continuous ballistocardiogram (BCG) sensor for cardiovascular monitoring," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, pp. 5030–5033, 2012, doi: 10.1109/EMBC.2012.6347123.

[9] M. Gardner, S. Randhawa, G. Malouf, and K. Reynolds, "A Wearable Ballistocardiography Device for Estimating Heart Rate During Positive Airway Pressure Therapy: Investigational Study Among the General Population," *JMIR Cardio*, vol. 5, no. 1, p. e26259, May 2021, doi: 10.2196/26259.

[10] P. Yousefian *et al.*, "Physiological Association between Limb Ballistocardiogram and Arterial Blood Pressure Waveforms: A Mathematical Model-Based Analysis," *Scientific Reports 2019 9:1*, vol. 9, no. 1, pp. 1–13, Mar. 2019, doi: 10.1038/s41598-019-41537-y.

[11] M. Liu, F. Jiang, H. Jiang, S. Ye, and H. Chen, "Low-power, noninvasive measurement system for wearable ballistocardiography in sitting and standing positions," *Comput Ind*, vol. 91, pp. 24–32, Oct. 2017, doi: 10.1016/J.COMPIND.2017.05.005.

[12] C. Woody. Characterization of an Adaptive Filter for the Analysis of Variable Latency Neuroelectric Signals. Med. Biol. Eng. 1967; 5(6) 539–54.

Address for correspondence:
José Alberto García-Limón
EETAC-UPC
c/Esteve Terradas 7, edif. C4, lab. 123.
08860 Castelldefels (Spain)
jose.alberto.garcia@upc.edu