2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) | 979-8-3503-2447-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMBC40787.2023.10340170

DR.BEAT: First Insights into a Study to Collect Baseline BCG Data with a Sensor-Based Wearable Prototype in Heart-Healthy Adults*

Marie Cathrine Wolf, Peter Klein, Ulf Kulau, Christoph Richter and Klaus-Hendrik Wolf

Abstract— **The DR.BEAT project aims at the further development of a measurement system for recording ballisto-cardiographic signals into a body-worn sensor system combined with extensive signal processing, data evaluation and visualization. With a first breadboard prototype, an explorative feasibility study for acquiring initial signals of healthy cardiac activity in adults was performed. This paper briefly presents the DR.BEAT project, the breadboard prototype, the study conducted, and initial insights into the study results. The signals obtained in the study exhibit the seismocardiographic characteristics as reported in the literature and form the basis for further development of the hardware as well as the pre-processing and automated analysis algorithms in the DR.BEAT project.**

Clinical Relevance— **The characteristics of ballisto- and seismocardiographic signals allow to infer about the mechanical work of the heart. The development of a body-worn sensor system to record ballisto- and seismocardiographic signals, compact enough for everyday wear, enables the acquisition of heart-specific parameters in terrestrial as well as extraterrestrial application scenarios. Combined with extensive signal analysis and visualization, it holds the potential to monitor heart health in a variety of contexts and support its maintenance and improvement.**

I. Introduction

The measurement method investigated is the ballisto-cardiography (BCG), which non-invasively measures the body's micromovements that occur during each heartbeat due to the recoil forces of blood flow along the vascular tree. The recording of these movements can be in the form of displacement, velocity, or acceleration signals and has features in all three spatial axes [1]. Seismocardiography (SCG) is a specialization of ballistocardiography that measures body motion non-invasively at the chest (usually at the sternum) [2]. Signals recorded at these positions near the heart are the result of heart contractions, valve movements, and blood flow, and are transmitted to the thorax surface [1].

The ballisto- and seismocardiographic signals enable non-invasive mapping of the mechanical work of the heart. Recent technical advancements allow for compact BCG measurement systems, enabling non-invasive monitoring of heart mechanics. Since there are fewer signal interferences in zero gravity, BCG is not only suitable for terrestrial but also for extraterrestrial monitoring.

The aim of this paper is to present the DR.BEAT project and the initially developed breadboard prototype as well as the implementation and first results of a feasibility study with heart-healthy adults using the breadboard prototype.

II. DR.BEAT Project

The project "DR.BEAT" (Digital Research on Ballisto-cardiography for extraterrestrial and terrestrial use), funded by the German Aerospace Center (DLR), is a collaboration between DSI Aerospace Technologie GmbH (DSI), Peter L. Reichertz Institute for Medical Informatics of TU Braunschweig and Hannover Medical School (PLRI), and UID GmbH (UID), each of which is responsible for the respective following project focal points. The project aims to improve a measurement system for recording BCG signals, developed in previous work [3], into a wearable BCG system. This further sensor system development (led by DSI), along with extensive signal processing, data evaluation (led by PLRI), and visualization (led by UID), will enable valid heart monitoring in both terrestrial and extraterrestrial scenarios.

A. Sensor System

The sensor system's development aims at a highly integrated, energy efficient sensor system for continuous measurement of acceleration in high data quality. To achieve this, the first development iteration focused on improving a measurement system for recording ballistocardiographic signals from previous work [3], resulting in a first breadboard prototype for the measurement of micro accelerations (cf. Fig. 1.). The prototype's sensor unit uses two triaxial accelerometers (Kionix-132) mounted in a differential arrangement on a printed circuit board to reduce noise and interference through differential signaling [4]. Additionally, the setup currently includes an OLIMEX SHIELD ECG-EMG to record a synchronized reference electrocardiogram (ECG) during the initial development phase, which will not be included in future hardware iterations. In the previous system the computing units of all sensors were combined in one bulky box. The current prototype includes two smaller boxes (79 mm x 76 mm

*Research supported by the German Aerospace Center (DLR), supervised by the Federal Ministry for Economic Affairs and Climate Action (BMWK); Funding Reference: 50RP2130C, and partly supported by the Lower Saxony "Vorab" of the Volkswagen Foundation, supervised by the Center for Digital Innovations (ZDIN) as well as the Ministry for Science and Culture of Lower Saxony; Grant No. ZN3491.

M. C. Wolf is with the Peter L. Reichertz Institute for Medical Informatics of TU Braunschweig and Hannover Medical School, 30625 Hannover, Germany (corresponding author to provide phone: +49 511 532-19331; fax: +49 511 532-19335; e-mail: marie.wolf@plri.de).

P. Klein is with the UID GmbH, 68161 Mannheim, Germany (e-mail: peter.klein@uid.com).

U. Kulau, is with the DSI Aerospace Technologie GmbH, 28199 Bremen, Germany (e-mail: ulf.kulau@dsi-as.de).

C. Richter, is with the DSI Aerospace Technologie GmbH, 28199 Bremen, Germany (e-mail: christoph.richter@dsi-as.de).

K.-H. Wolf is with the the Peter L. Reichertz Institute for Medical Informatics of TU Braunschweig and Hannover Medical School, 30625 Hannover, Germany (e-mail: klaus-hendrik.wolf@plri.de).

x 32 mm each) for the computing units of the 3D-acceleration and the ECG. The recording of the sensor data (3D-accelerations (X-axis, Y-axis, Z-axis) as well as ECG) is done with a sampling rate of 1 kHz. The recorded data (header, 3D-accelerations, ECG) are written to an SD card, which can be read out after the measurement is finished. Data transfer using the implemented Bluetooth low energy (BLE) is not possible at this stage due to the additional data load provided by the ECG, but will be targeted for the next study phase.

In addition to the planned hardware modifications mentioned above, the further development of the first prototype will be based, among other things, on the results of initial test measurements on humans.

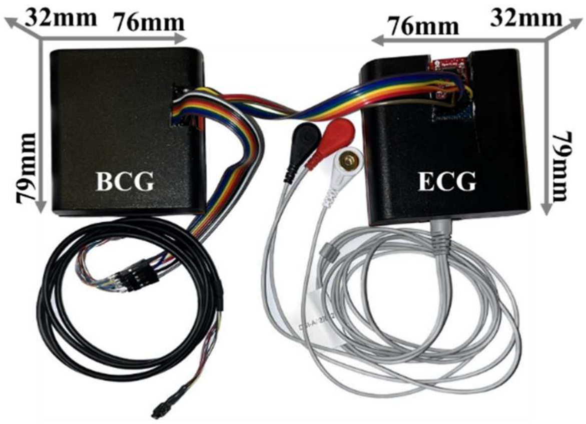

Figure 1. First breadboard prototype for the measurement of micro accelerations

B. Signal Processing and Data Evaluation

The goal of the project part "signal processing and data evaluation" is to create reference data through test measurements, which will serve as the foundation for extensive data analysis. In addition, the automation of data analysis (feature detection) and the implementation of AI-supported signal evaluation based on the resulting data will be carried out.

For data collection, the DR.BEAT project aims at a study phase with the here described breadboard prototype as well as a later study phase with a more advanced iteration of the prototype.

C. Visualization

The visualization scope includes designing an user interface with optimal user experience. The focus is on supporting three terrestrial application scenarios: The "Data Analyst" scenario supports research of BCG signals. "Quantify Yourself" involves using a BCG wearable for signal processing, visualization and analytics in fitness and wellness to support heart health enhancing lifestyle decisions. The third application scenario "Medical Use" examines support for monitoring heart health in medical contexts. [9]

In addition to terrestrial scenarios, the extraterrestrial application is considered, including telemedical monitoring of astronauts during manned space flight.

To focus on the user in the development of the BCG wearable and post-project concepts, visualization development uses Scenario-Based Design methods [10].

III. Study

An exploratory feasibility study using the described breadboard prototype was performed with heart-healthy adults in the first study phase, with a positive ethics vote from the ethics committee of faculty 2 of TU Braunschweig (Chair: Prof. Dr. Mark Vollrath; identification number: D_2022_10).

The primary endpoint of the study was the collection of baseline ballistocardiography data from heart-healthy adults using the prototype to create the targeted reference data sets, which will be used for internal project development as well as made available to other research groups for BCG and SCG research. Secondary endpoints considered included examining the signal quality of the collected baseline ballistocardiography data and examining the comparability of the data with existing data sets.

According to the study plan, a total of 12 study participants (6 male and 6 female) aged 18 to 59 years were targeted for measurements. The study participants must not have any known cardiac diseases, past or planned cardiac surgery or be on medication that affect the heart. Furthermore, no smokers or regular alcohol consumers were included in the study. Participants could not be severely overweight or underweight (body mass index (BMI) > 18.5 and BMI < 30), and had to be able to give consent and to complete the study.

A. Study Execution

Data collection began after obtaining verbal and written informed consent from participants, starting with a questionnaire, which served for the final verification of the inclusion and exclusion criteria as well as for the collection of information that may have an influence on the signal (age, BMI, gender). After questionnaire administration, the measurement system with the three ECG electrodes was attached to the positions according to Einthoven. The acceleration sensor unit was attached to the sternum of the study participants (as seen in the Fig. 2.), using medical tape. The positioning of the acceleration sensor unit close to the heart was intended to allow the recording of seismocardiographic signals.

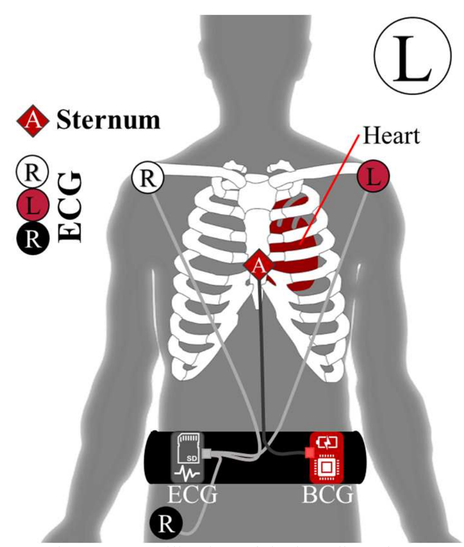

Figure 2. Study setup – Utilization of the breadboard prototype for seismocardiographic measurements

A measurement was then started in which the study participants performed different activities: The measurement began with 3 minutes of sitting. The participants were then asked to stand up and remain standing for 2 minutes. This was followed by 7 minutes of walking at a comfortable speed similar to everyday life. After that, participants were asked to stand still for another 3 minutes. The measurement was concluded with 5 minutes of sitting. Participants were instructed to avoid any actions that may disturb the measurement, such as talking, coughing, sneezing or clearing the throat.

After completion of the individual measurements, the recorded data set was immediately reviewed visually to ensure that no errors occurred during the measurement setup or with the measurement system, thus ensuring comparable data series.

B. *Data Processing and First Evaluation*

The pre-processing started with the calibration of the sensor data (acceleration and ECG data). For the calibration of the acceleration data, 3D-ellipsoid fitting methods [11] were used. The acceleration and ECG data were then smoothed using a rolling mean with a window width of 20 values (equivalent to 20 ms) to minimize noise and signal interference. The smoothed data were filtered to extract heart-specific frequencies and remove noise using a third-order Butterworth bandpass filter with a frequency range of 20 Hz to 35 Hz for SCG signals and a second-order Chebyshev bandpass filter with cutoff frequencies of 1 Hz and 20 Hz for ECG data [12]. The applied filtering methods were based on the methods of previous work [13], but the cutoff frequencies were adapted to remove more noise from the signal.

To classify rest and motion phases, the differences between the values of the calibrated acceleration data were squared to distinguish higher accelerations of the motion phase (walking) from lower accelerations in the rest phases (sitting and standing). The squared differences of the acceleration data were again smoothed using a rolling mean with a window width of 1,000 values (equivalent to one second) to obtain only crucial activity differences and exclude fine accelerations changes. Subsequently, a fixed limit of twice the mean difference between the individual values plus the standard deviation was used to annotate rest and motion phases.

For a first insight into the study data, the heartbeats were detected automatically by identifying R-peaks in the filtered ECG data (R-package 'rsleep', function 'detect_rpeaks', version 1.0.6 [13]). Heartbeat sequences were segmented from 200 ms before the occurring R-peak, to include the complete ECG's QRS complex into the segment, to the next detected R-peak.

To minimize the impact of intra- and interindividual differences and enable comparability with existing data sets, the segmented heartbeat sequences of the ECG as well as SCG (X-axis, Y-axis and Z-axis) data were averaged. This process generated three sets of data per subject: an average signal for all heartbeats in the measurement, for all heartbeats in the classified rest phases, and for all heartbeats in the classified physical stress phase. Furthermore, these averaged signals from all study participants were averaged again. This generated nine sets of data: an average signal for all heartbeats, for all heartbeats in the classified rest phases, and for all heartbeats in the classified physical stress phases, for all study participants (n=12) and for all female and male participants (n=6 each), respectively.

IV. Results

Six females and six males aged 20 to 31 years were included in the study (further description: see Table I.).

The averaged signals of the heartbeats over all study participants were averaged over approximately 20,000 heartbeats (approx. 1,650 heartbeats per participant). These can be divided into approximately 9,300 heartbeats at rest (approx. 700 heartbeats per participant) and approximately 10,700 heartbeats under physical stress (approx. 900 heartbeats per participant).

By comparing the resulting averaged signal over all heartbeats, the expected signal characteristics from the literature [1] could be detected and thus manually annotated in the averaged signal (cf. Fig. 3.). Additionally, the averaged signals of the heartbeat sequences differentiated in rest and physical stress showed that the expected signal features were recognized, but the amplitudes of the signal features under physical stress were higher compared to those at rest (cf. Fig. 4.).

TABLE I. DESCRIPTION OF STUDY POPULATION

	Age (years)	**Weight (kg)**	**Height (cm)**	**BMI (kg/m²)**
Min	20.00	59.70	164.00	21.66
Mean	25.42	75.93	176.25	24.37
STD	3.30	8.73	7.71	1.58
Max	31.00	85.20	189.00	27.62

V. Discussion

The pre-processing presented in this work was based on adapted methods of previous work [13]. The current state of research already investigates more comprehensive methods for denoising and filtering of BCG and SCG signals (e. g. [11, 12]) as well as for signal evaluation (e. g. without ECG reference [13] or supported by artificial intelligence methods [14]).

For the intended first insight into the study data as preparation for adaptation of the automated evaluation algorithms, the described approach provides sufficient results. Adaptation to the currently researched methods not only allows more precise evaluation results but also an improved suitability for everyday use due to independence from a reference and thus the possibility of further minimization of the hardware setup.

Nevertheless, the use of a synchronized reference ECG is suitable for this study phase to validate heartbeats detected from SCG, which allows testing and initial validation when adapting automated evaluation algorithms. Furthermore, the interpretability of the ECG allows to derive new findings about SCG signals which adds value to the recorded data sets for SCG research.

VI. Conclusion

In conclusion, the breadboard prototype used in this study was able to successfully record seismocardiographic signals that match the expected signal characteristics from literature.

The data collected over a total of 240 minutes and approximately 20,000 heartbeats in this study phase forms the basis for the reference data in the DR.BEAT project. In future work, the signal pre-processing and automated signal evaluation will be improved and adapted to the current state of research to enable the analysis of SCG signals without reference ECG. Additionally, the system will be miniaturized for the next hardware iteration, and a validation study for the automated algorithms will be conducted.

APPENDIX

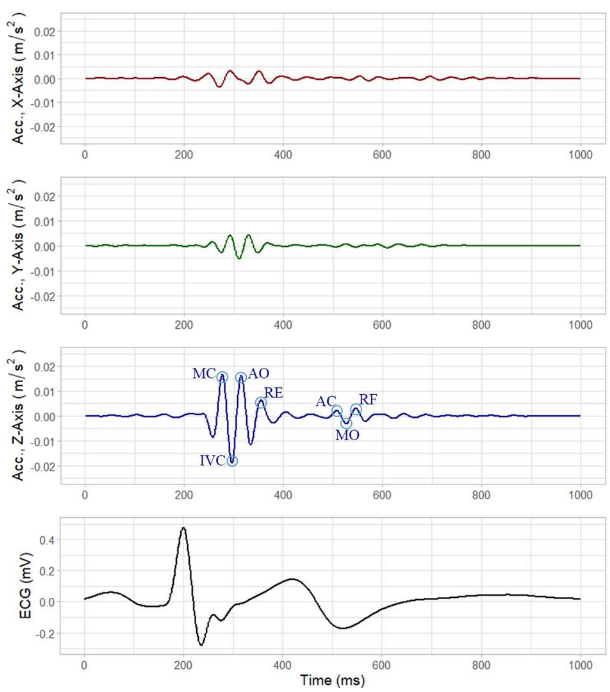

Figure 3. Averaged acceleration (Acc.) and electrocardiographic (ECG) signals over all heartbeats with annotated seismocardiographic features in Acc., z-axis

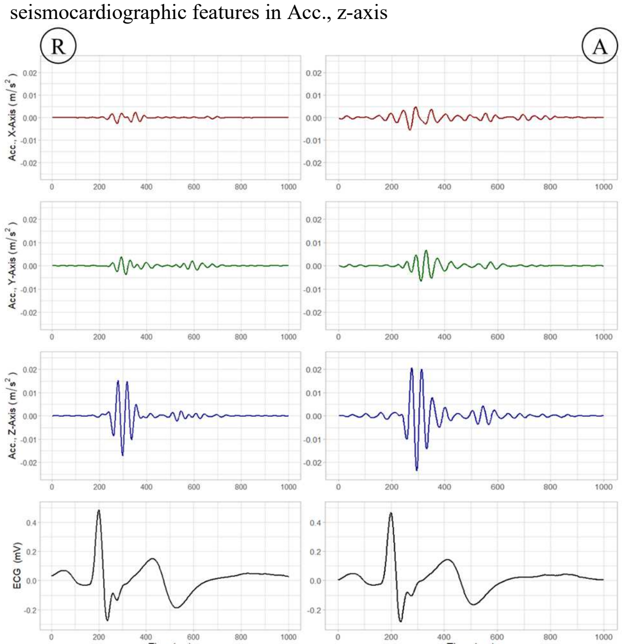

Figure 4. Averaged acceleration (Acc.) and electrocardiographic (ECG) signals over all heartbeats differentiated in rest (R) and activity (A)

REFERENCES

[1] O. T. Inan, P.-F. Migeotte, K.-S. Park, M. Etemadi, K. Tavakolian, R. Casanella, J. Zanetti, J. Tank, I. Funtova, G. K. Prisk and M. D. Rienzo, "Ballistocardiography and Seismocardiography: A Review of Recent Advances," *IEEE Journal of Biomedical and Health Informatics,* vol. 19, p. 1414–1427, July 2015.

[2] A. Taebi, B. Solar, A. Bomar, R. Sandler and H. Mansy, "Recent Advances in Seismocardiography," *Vibration,* vol. 2, p. 64–86, January 2019.

[3] T. Clausen, T. Jura, N. Jähne-Raden, M. C. Wolf, L. Wolf and U. Kulau, "A Precise, Parallel and Scalable Measurement System for Ballistocardiographic Research," *Smart Health,* vol. 19, p. 100169, March 2021.

[4] U. Kulau, J. Rust, D. Szafranski, M. Drobczyk and U.-V. Albrecht, "A Differential BCG Sensor System for Long Term Health Monitoring Experiment on the ISS," in *18th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, 2022.

[5] M. C. Wolf, C. Hintz, P. Klein, D. Zenth, U. Kulau, C. Richter and K.-H. Wolf, "Anforderungen an ein ballistokardiographisches Sensorsystem zur terrestrischen und extraterrestrischen Verwendung," in *67. Jahrestagung der Deutschen Gesellschaft für Medizinische Informatik, Biometrie und Epidemiologie e. V. (GMDS), 13. Jahreskongress der Technologie- und Methodenplattform für die vernetzte medizinische Forschung e. V. (TMF)*, 2022.

[6] M. B. C. J. M. Rosson, "The human-computerinteraction handbook: Fundamentals, evolving technologies, and emerging applications.," A. S. J. Jacko, Ed., Lawrence Erlbaum Associates, 2003, pp. 1032-1048.

[7] M. Gietzelt, K.-H. Wolf, M. Marschollek and R. Haux, "Performance comparison of accelerometer calibration algorithms based on 3D-ellipsoid fitting methods," *Computer Methods and Programs in Biomedicine,* vol. 111, p. 62–71, July 2013.

[8] U. Ligges, T. Short, P. Kienzle, S. Schnackenberg, D. Billinghurst, H.-W. Borchers, A. Carezia, P. Dupuis, J. W. Eaton, E. Farhi, K. Habel, K. Hornik, S. Krey, B. Lash, F. Leisch, O. Mersmann, P. Neis, J. Ruohio, I. I. I. Julius O. Smith, D. Stewart and A. Weingessel, *Package 'signal': Signal Processing,* 2021.

[9] N. Raden, "Konzeption eines neuen ballistokardiographischen Verfahrens zur Untersuchung kardiovaskulärer Vorgänge sowie der pathologischen Abgrenzung am Beispiel der Herzinsuffizienz," Universitätsbibliothek Braunschweig, 2021.

[10] P. Bouchequet, G. Solelhac and D. Leger, "rsleep, un package R open-source pour l'analyse des polysomnographies," *Médecine du Sommeil,* vol. 17, p. 67, March 2020.

[11] D. J. Lin, J. P. Kimball, J. Zia, V. G. Ganti and O. T. Inan, "Reducing the Impact of External Vibrations on Fiducial Point Detection in Seismocardiogram Signals," *IEEE Transactions on Biomedical Engineering,* vol. 69, p. 176–185, January 2022.

[12] B. M. Manjula and C. Sharma, "Ballistocardiography signal filtering using adaptive least mean square algorithm," in *IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, 2016.

[13] L. Luu and A. Dinh, "Using Moving Average Method to Recognize Systole and Diastole on Seismocardiogram without ECG Signal," in *40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2018.

[14] H. Lu, H. Zhang, Z. Lin and N. S. Huat, "A Novel Deep Learning based Neural Network for Heartbeat Detection in Ballistocardiograph," in *40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2018.