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Performance improvement of cardiorespiratory measurements using pressure sensors with mechanical coupling techniques

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Abstract

Monitoring heart rate and breathing is essential in understanding the physiological processes for sleep analysis. Polysomnography (PSG) system have traditionally been used for sleep monitoring, but alternative methods can help to make sleep monitoring more portable in someone's home. This study conducted a series of experiments to investigate the use of pressure sensors placed under the bed as an alternative to PSG for monitoring heart rate and breathing during sleep. The following sets of experiments involved the addition of small rubber domes - transparent and black - that were glued to the pressure sensor. The resulting data were compared with the PSG system to determine the accuracy of the pressure sensor readings. The study found that the pressure sensor provided reliable data for extracting heart rate and respiration rate, with mean absolute errors (MAE) of 2.32 and 3.24 for respiration and heart rate, respectively. However, the addition of small rubber hemispheres did not significantly improve the accuracy of the readings, with MAEs of 2.3 bpm and 7.56 breaths per minute for respiration rate and heart rate, respectively. The findings of this study suggest that pressure sensors placed under the bed may serve as a viable alternative to traditional PSG systems for monitoring heart rate and breathing during sleep. These sensors provide a more comfortable and non-invasive method of sleep monitoring. However, the addition of small rubber domes did not significantly enhance the accuracy of the readings, indicating that it may not be a worthwhile addition to the pressure sensor system.

Keywords: FSR sensors, elastic domes, Polysomnography system (PSG), signal processing, heart rate, respiratory rate.

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1. Introduction

Cardiorespiratory monitoring during sleep is crucial for diagnosing and treating various sleep disorders and understanding the role of sleep in overall health and well-being [1-3]. Polysomnography (PSG) is considered the gold standard method for measuring cardiorespiratory activity during sleep [4-5]. However, PSG is invasive, expensive, and time-consuming. In recent years, non-invasive research methods have been developed to improve the accessibility and convenience of cardiorespiratory monitoring, including using pressure sensors under the mattress to measure heartbeat and breathing rate [6-7].

The use of pressure sensors as a non-invasive method for measuring cardiorespiratory activity during sleep has been investigated in several previous studies. For example, a study [8] found that pressure sensors placed under the mattress can provide reliable measures of respiratory events during sleep, with a high level of agreement with PSG. Another study [9] investigated the use of pressure sensors to measure sleep quality in patients with obstructive sleep apnea and found that pressure sensors were a feasible and reliable alternative to PSG.

Although pressure sensors are an effective method for measuring cardiorespiratory activity during sleep [10], there are still limitations to the accuracy and reliability of the measurements. One limitation is the mechanical coupling between the pressure sensor and the mattress surface. To address this limitation, various mechanical coupling techniques have been investigated, such as using hemispheres as an interface between the pressure sensor and the mattress surface.

In this study, we aimed to investigate the potential benefits of using hemispheres to improve the performance of pressure sensors in measuring cardiorespiratory activity [11-12]. Specifically, we explored using two hemispheres: transparent and black domes. These hemispheres have different material.

Our study focused on comparing the accuracy of cardiorespiratory measurements obtained using pressure sensors with and without hemispheres and comparing the accuracy of these measurements to those obtained via PSG [13]. We used the mean absolute error (MAE) and Bland–Altman analyses [14] as a metric to compare the accuracy of the measurements obtained with and without hemispheres. Our findings suggest that the use of hemispheres did not significantly improve the accuracy of the measurements compared to the results obtained without them.

Our study provides insight into the potential benefits and limitations of using pressure sensors and mechanical coupling techniques for non-invasive cardiorespiratory monitoring during sleep. The results of our study are consistent with previous research showing the feasibility and reliability of pressure sensors in measuring cardiorespiratory activity during sleep. However, the use of domes did not appear to provide any significant improvement in the accuracy of these measurements. Our study contributes to the growing research to develop non-invasive methods for measuring cardiorespiratory activity during sleep.

2. Methods and materials

2.1. Hardware system

The hardware setup system used in the study consisted of:

- 2 FSR 408 Strip sensors[2]. The standard 408 sensor is a strip sensor 622.3 mm in length. Actuation force as low as 0.1 N and sensitivity range to 10 N. The sensors are located under the mattress on the bed net to cover the thoracic (D1) and abdominal (D2) regions of subjects (see Figure 1);
- 10 transparent domes (d=20mm), transparent self-adhesive protective buffers are made from a permanently elastic plastic for the best buffer properties, simple, and odorless. Glued on linear sensors (5 on each) along the entire length (see Figure 1a);
- 10 black domes (d=20mm), soft rubber elastic. Glued on linear sensors (5 on each) along the entire length (see Figure 1b);

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[2] from Interlink Electronics, California, USA

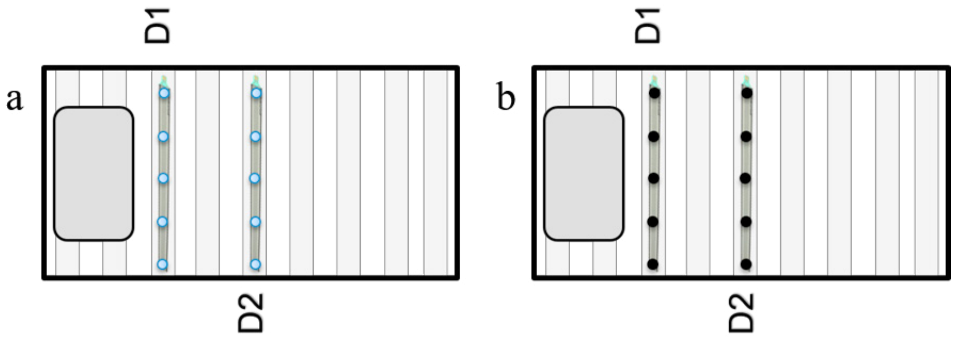

Figure 1. Top view. D1 and D2 sensor distribution. (a) transparent domes on the sensors; (b) black domes on the sensors.

In addition, the system included two amplification boards, one analog-to-digital converter (ADC) board, and an ADC to an inter-integrated circuit (IIC) interfacing converter. In this research, the ADS1015[3] converter has been used. The amplification boards were used to amplify the signals from the sensors, and the ADC board was used to convert the analog signals to digital signals. The APDC to IIC interfacing converter connected the ADC board to the microcomputer/microprocessor. Raspberry Pi 4B[4] with 4GB RAM and 32 GB external memory has been chosen as a computational unit for the system. The electrical circuit used in this paper was previously presented during the design of the personal health system in Long-Term Care [15]. This circuit includes the power supply stabilization, the voltage divider circuit with amplifier gain and the active low-pass filter in the hardware setup. The embedded system was used to collect and process the data from the sensors and store it for analysis (see Figure 2).

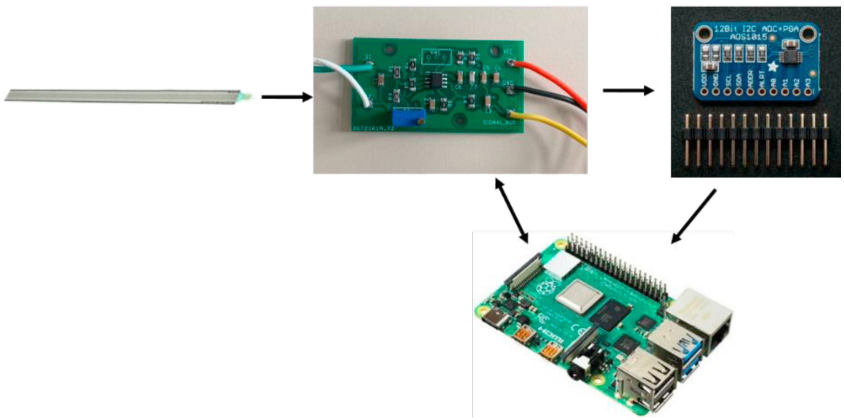

Figure 2. Structure scheme of the hardware system.

2.2. Experiment design

In the study, four healthy subjects participated and provided informed consent. The subjects were instructed to lie down in four regular sleeping positions (prone, right lateral, supine, and left lateral) see Figure 3(a), and data were collected for 140 seconds in each position. The subjects were instructed to behave normally with minimal movement

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[3] Technical details - https://www.adafruit.com/product/1083#technical-details
[4] Raspberry Pi Foundation, Cambridge, UK

during the data collection but were advised that the experiment would be stopped if they experienced any discomfort.

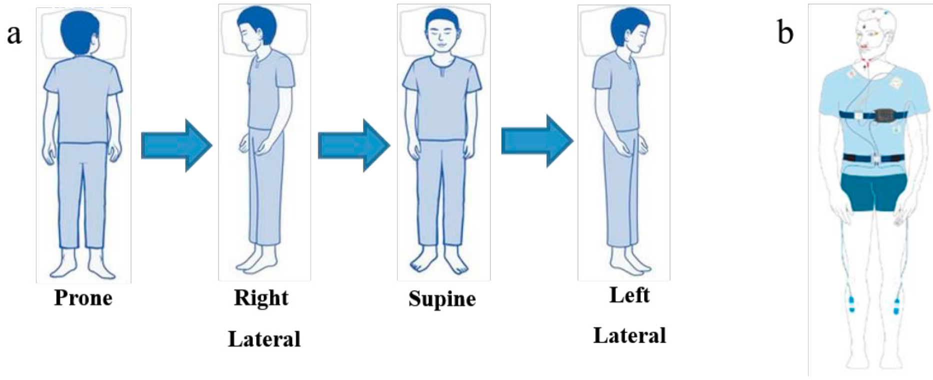

Figure 3. (a) all four regular sleeping positions; (b) PSG system.

2.3. Data acquisition

For reference data, a PSG system[5] was used, which included a two-electrode ECG and a Respiratory Inductive Plethysmography (RIP) belt for thorax (THO) and abdomen (ABD) signal recording (see Figure 3b). The ECG, respiration rate, and FSR sensors were recorded at 256 Hz, 32 Hz, and 160 Hz, respectively (see Figure 4).

2.4. Data pre-processing and processing

To analyze the data obtained from the FSR sensors and PSG system, pre-processing was performed with the following steps:

- The data received from the PSG and FSR systems were time-synchronized since they had different timestamps.
- Four windows were created, each corresponding to the patient's position on the bed, with a duration of two minutes each. The data's first and last ten seconds were removed from each position to obtain a clean signal.

[5] from SOMNOmedics GmbH in Randersacker, Germany

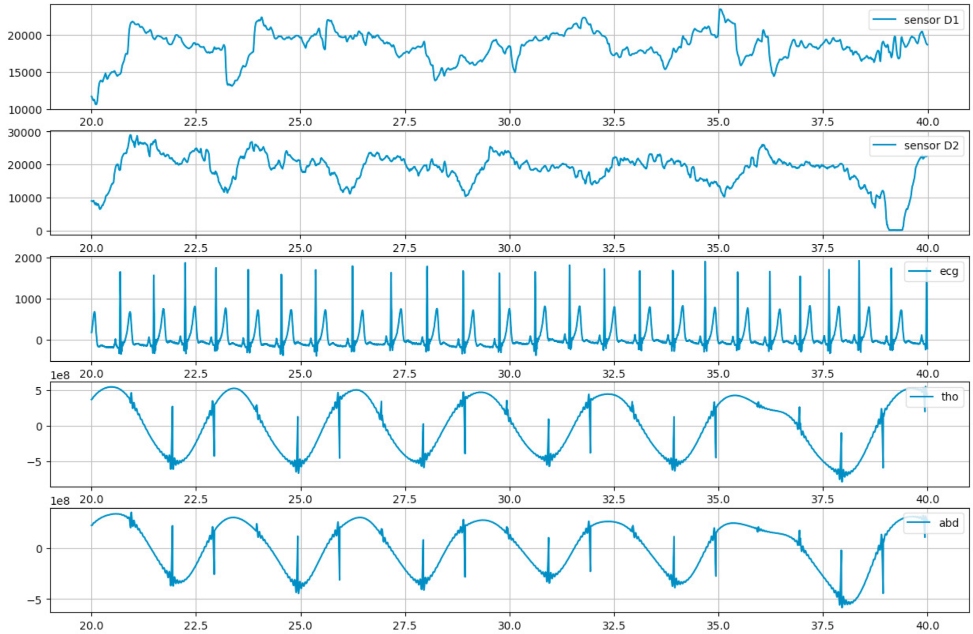

Figure 4. Example at 20 seconds of all raw data

The processing of the data involved breaking it down into 20-second epochs. The data was then analyzed using a second-order Butterworth filter with band-pass filter cut-off frequencies of [0.15; 0.4] Hz to estimate RR from the FSR sensor data [16-17]. A peak detector was then used to identify the respiratory peaks. For HR calculation, a Chebyshev type I band-pass filter with lower and higher cutoff frequencies of [2.5; 5] Hz was used in the first step. Multi-resolution analysis was then performed using the maximal overlap discrete wavelet transform. The wavelet biorthogonal 3.9 basis function was chosen with a decomposition level of 4 for HR estimation [18], which was determined after several trials before the actual data acquisition. The frequency of the maximum peaks in the data aligned with the frequency of the cardiac cycles (see Figure 5).

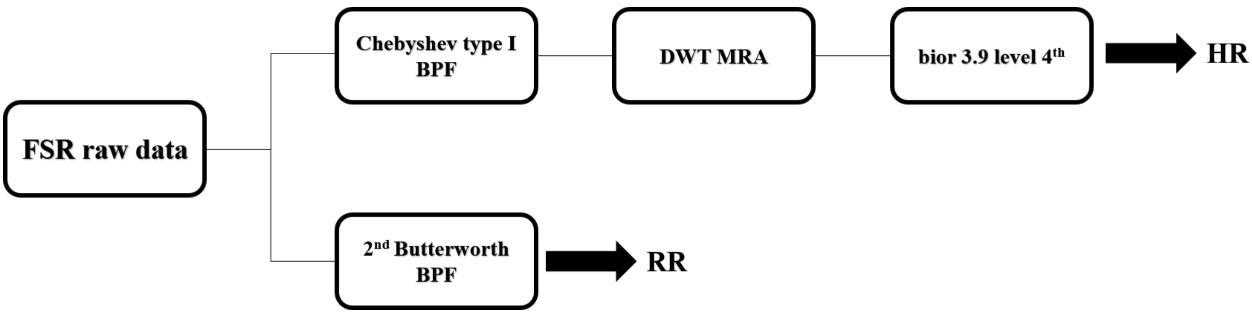

Figure 5. Signal processing was performed in two pipelines.

To evaluate the analysis results, we utilized two metrics, namely the mean absolute error (MAE) and the Bland-Altman limit of agreement (LoA).

3. Results

Based on the analysis of respiration rate and heartbeat in 2 experiments involving transparent and black domes, the following results were obtained:

For respiration rate, the mean absolute error was 2.21 (sensor D1) and 2.33 (sensor D2) for transparent hemispheres and 2.5 (sensor D1) and 2.18 (sensor D2) for black hemispheres. The limits of agreement (LoA) for all subjects were in the range of [-6.31, 5.96] for transparent hemispheres (sensor D1), and [-6.17, 5.90] for transparent hemispheres (sensor D2), [-6.86, 5.65] for black hemispheres (sensor D1), [-5.93, 5.47] for black hemispheres (sensor D2).

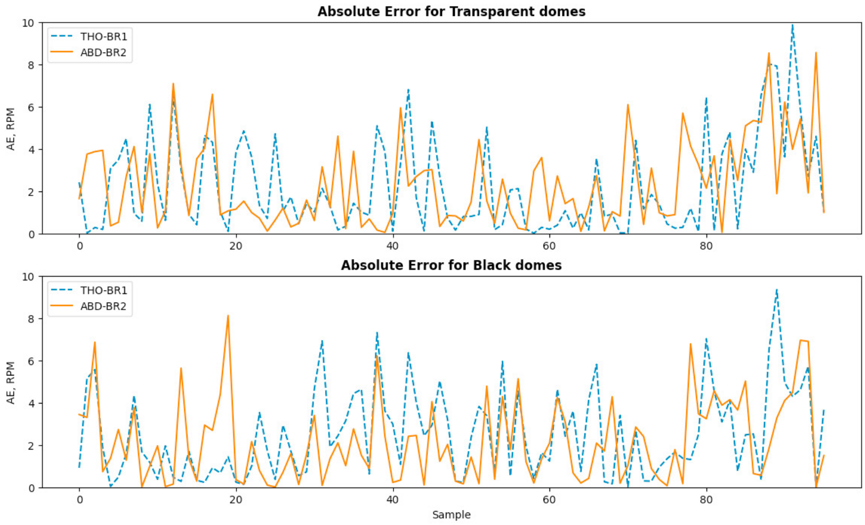

Figure 6. Absolute error for transparent and black domes for respiratory rate.

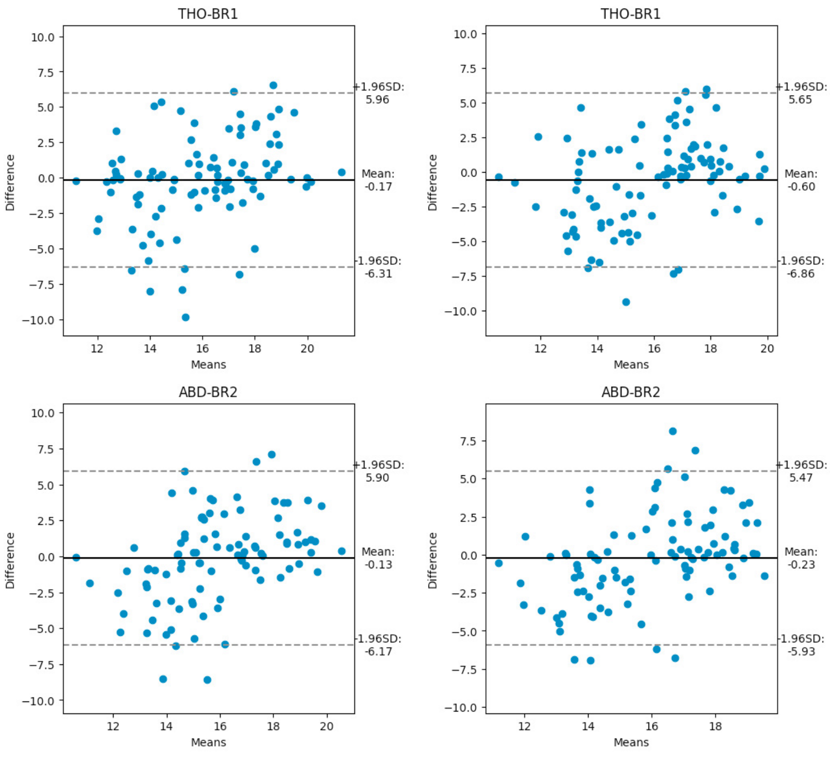

Figure 7. The LoA between the respiratory estimation of transparent domes (left) and black domes (right). From top to bottom: LoA of the thoracic (and sensor D1) and abdominal (and sensor D2) regions.

For heartbeat, the mean absolute error was 7.56 (sensor D1) and 7.87 (sensor D2) for black hemispheres and 7.59 (sensor D1) and 7.2 (sensor D2) for transparent hemispheres. The LoA for all subjects were in the range of [-19.44, 9.21] for black hemispheres (sensor D1), [-20.57, 9.95] for black hemispheres (sensor D2), [-20.04, 13.21] for transparent hemispheres (sensor D1), and [-19.88, 14.30] for transparent hemispheres (sensor D2).

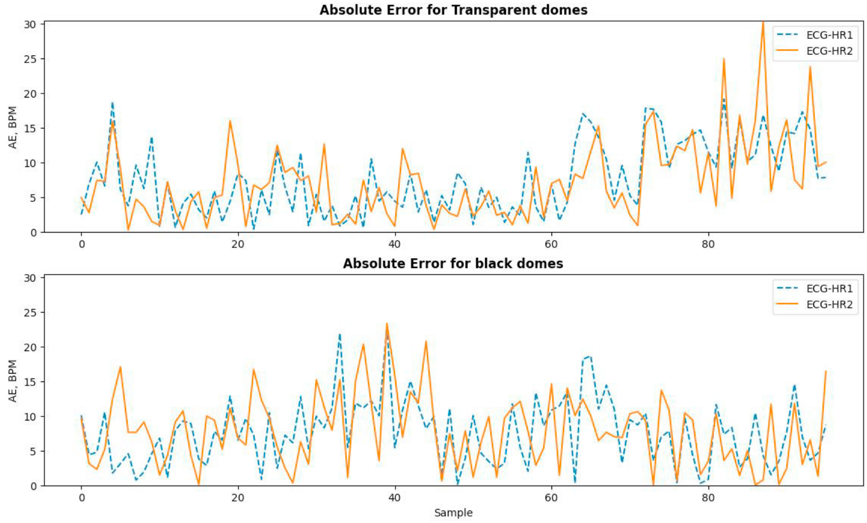

Figure 8. Absolute error for transparent and black domes for heart rate.

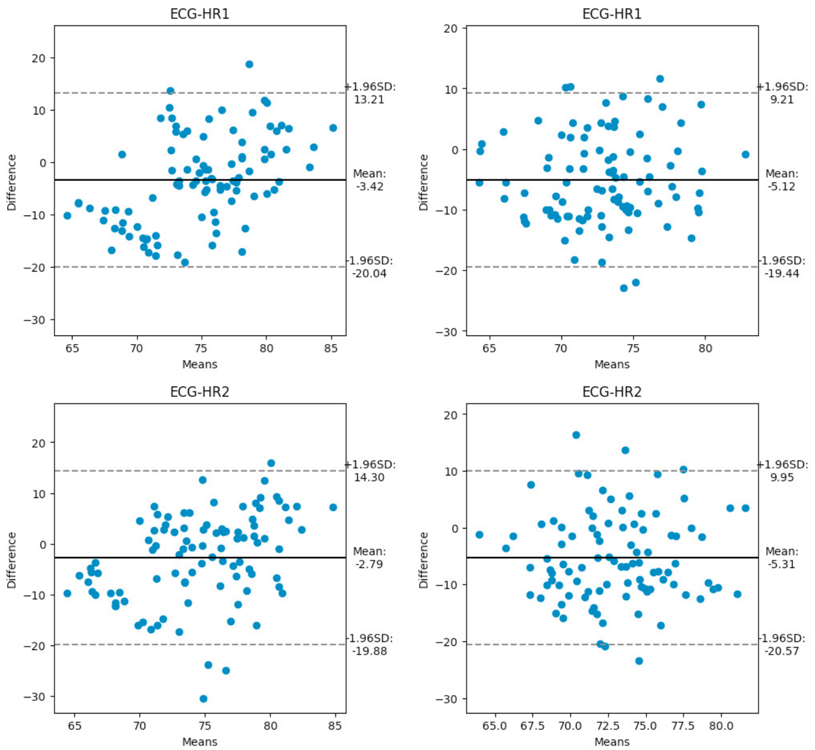

Figure 9. The LoA between the heart rate estimation of transparent domes (left) and black domes (right). From top to bottom: LoA of the ECG (and sensor D1) and ECG (and sensor D2) signals.

These results suggest that the transparent hemispheres may have slightly better accuracy in measuring respiration rate and heartbeat than the black hemispheres, as indicated by the lower mean absolute error values. However, there is some overlap in the LoA ranges for both types of hemispheres, suggesting that the differences in accuracy may not be significant. It is important to note that these findings are based on a relatively small sample size of 4 participants in each experiment.

It is worth noting that compared with previous experiments conducted without the use of hemispheres, the addition of hemispheres did not appear to improve the accuracy of the measurements in all cases. The use of hemispheres resulted in a slight decrease in accuracy for measuring heartbeat in both hemispheres, as indicated by the higher mean absolute error values and wider LoA ranges compared to previous experiments. However, for respiration rate, the use of hemispheres did not result in a significant improvement or deterioration of accuracy, with mean absolute error values remaining within a similar range. These results suggest that adding hemispheres may not always lead to improved accuracy.

4. Conclusion

In conclusion, the analysis of respiration rate and heartbeat in two experiments involving black and transparent hemispheres showed that both types of hemispheres could be used to accurately measure physiological signals, with some slight differences in accuracy between them. The transparent hemispheres showed slightly better accuracy in measuring both respiration rate and heartbeat, as indicated by the lower mean absolute error values. However, the differences in accuracy may not be significant as there is some overlap in the LoA ranges for both types of hemispheres.

These findings suggest that black and transparent hemispheres are viable for measuring physiological signals. The choice between them may depend on other factors such as cost, availability, and specific research needs. It is important to note that the results are based on a relatively small sample size of 4 participants in each experiment. Further research with larger sample sizes may be necessary to confirm these findings.

Overall, the study highlights the importance of careful selection and validation of measurement devices for accurate and reliable measurement of physiological signals in research and clinical settings.

There are several potential methods for future work to increase the number of hemispheres used in future studies. One approach is to reduce the radius of the domes so that only the part detected by the sensor is touched. Another is to increase the number of participants in the study, which would allow for a larger sample size and a more thorough analysis of the accuracy and reliability of the physiological signal measurements. These approaches could provide valuable insights into the effectiveness of hemispheres in measuring physiological signals and help optimize the use of this technology in research settings.

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References

[1] Worley, Susan L. "The extraordinary importance of sleep: the detrimental effects of inadequate sleep on health and public safety drive an explosion of sleep research." Pharmacy and Therapeutics 43.12 (2018): 758.

[2] Knutson, K. L., Phelan, J., Paskow, M. J., Roach, A., Whiton, K., Langer, G., ... & Hirshkowitz, M. (2017). The National Sleep Foundation's sleep health index. Sleep health, 3(4), 234-240.

[3] National Heart Lung and Blood Institute (NHLBI) 2011 Your Guide to Healthy Sleep (NIH Publication No. 11-5271) (Bethesda, MD: National Heart, Lung, and Blood Institute).

[4] Hall, Andrew. "Sleep physiology and the perioperative care of patients with sleep disorders." BJA Education 15.4 (2015): 167-172.

[5] Electronic resource. Psychiatry Data Base. Polysomnography (PSG) Access: https://www.psychdb.com/neurology/polysomnography#polysomnography-psg. Date of access: 10.04.2023.

[6] Berry, R. B., Brooks, R., Gamaldo, C. E., Harding, S. M., Marcus, C., & Vaughn, B. V. (2012). The AASM manual for the scoring of sleep and associated events. Rules, Terminology and Technical Specifications, Darien, Illinois, American Academy of Sleep Medicine, 176, 2012.

[7] Ibáñez, Vanessa, Josep Silva, and Omar Cauli. "A survey on sleep assessment methods." PeerJ 6 (2018): e4849.

[8] Gaiduk, M., Kuhn, I., Seepold, R., Ortega, J. A., & Martínez Madrid, N. (2017, April). A sensor grid for pressure and movement detection supporting sleep phase analysis. In International Conference on Bioinformatics and Biomedical Engineering (pp. 596-607). Springer, Cham.

[9] Gaiduk, M., Weber, L., Alarcón, Á. S., Seepold, R., Martínez Madrid, N., Orcioni, S., & Conti, M. (2021). Design of a sleep apnoea detection system for a home environment. Procedia computer science, 192, 3225-3234.1.

[10] Gaiduk, M., Seepold, R., Martínez Madrid, N., Orcioni, S., & Conti, M. (2019, September). Recognizing breathing rate and movement while sleeping in home environment. In International Conference on Applications in Electronics Pervading Industry, Environment and Society (pp. 333-339). Springer, Cham.

[11] Andreozzi, E., Fratini, A., Esposito, D., Naik, G., Polley, C., Gargiulo, G. D., & Bifulco, P. (2020). Forcecardiography: A novel technique to measure heart mechanical vibrations onto the chest wall. Sensors, 20(14), 3885.

[12] Andreozzi, E., Gargiulo, G. D., Esposito, D., & Bifulco, P. (2021). A novel broadband forcecardiography sensor for simultaneous monitoring of respiration, infrasonic cardiac vibrations and heart sounds. Frontiers in Physiology, 1988.

[13] Haghi M, Asadov A, Boiko A, Ortega JA, Martínez Madrid N, Seepold R. Validating Force Sensitive Resistor Strip Sensors for Cardiorespiratory Measurement during Sleep: A Preliminary Study. Sensors. 2023; 23(8):3973. https://doi.org/10.3390/s23083973

[14] Giavarina, D. (2015). Understanding bland altman analysis. Biochemia medica, 25(2), 141-151.

[15] Boiko, A., Asadov, A., Gaiduk, M., Seepold, R., & Madrid, N. M. (2022, October). Gamification system to improve the personal health of bedridden patients in long-term care. In Social Innovation in Long-Term Care Through Digitalization: Proceedings of the German-Italian Workshop LTC-2021 (pp. 127-139). Cham: Springer International Publishing.

[16] Boiko, A., Scherz, W. D., Gaiduk, M., Gentili, A., Conti, M., Orcioni, S., ... & Madrid, N. M. (2022, November). Sleep respiration rate detection using an accelerometer sensor with special holder setup. In 2022 E-Health and Bioengineering Conference (EHB) (pp. 01-04). IEEE.

[17] Prigent, G., Aminian, K., Rodrigues, T., Vesin, J. M., Millet, G. P., Falbriard, M., ... & Paraschiv-Ionescu, A. (2021). Indirect estimation of breathing rate from heart rate monitoring system during running. Sensors, 21(16), 5651.

[18] Sadek, I., Biswas, J., Abdulrazak, B., Haihong, Z., & Mokhtari, M. (2017, February). Continuous and unconstrained vital signs monitoring with ballistocardiogram sensors in headrest position. In 2017 IEEE EMBS International Conference on Biomedical & Health Informatics (BHI) (pp. 289-292). IEEE.