Hardware and Software supporting Physiological Measurement (HSPM-2022)

Hardware and Software Supporting Physiological Measurement Workshop

October 27-28, 2022

Konstanz, Germany

Edited by

Ángel Serrano Alarcón and Andrei Boiko

Determination of Accelerometer Sensor Position for Respiration Rate Detection: Initial Research

Andrei Boiko[1] [0000-0002-6683-8485], Ralf Seepold[1] [0000-0002-5192-2537] and
Natividad Martínez Madrid[2] [0000-0003-1965-9481]

Abstract*. Continuous monitoring of a patient's vital signs is essential in many chronic illnesses. The respiratory rate (RR) is one of the vital signs indicating breathing diseases. This article proposes the initial investigation for determining the accelerometric sensor position of a non-invasive and unobtrusive respiratory rate monitoring system. This research aims to determine the sensor position in relation to the patient, which can provide the most accurate values of the mentioned physiological parameter. In order to achieve the result, the particular system setup, including a mechanical sensor holder construction was used. The breathing signals from 5 participants were analyzed corresponding to the relaxed state. The main criterion for selecting a suitable sensor position was each patient's average acceleration amplitude excursion, which corresponds to the respiratory signal. As a result, we provided one more defined important parameter for the considered system, which was not determined before.

Keywords -- contactless measurement, respiration rate, accelerometer sensor.

I. Introduction

One important aspect essential to the healthcare service is the continuous monitoring of the patient's vital signs. This can be done both in the hospital and on an ambulatory basis. However, regular monitoring becomes a barrier to the patient's everyday life. The creation, implementation, and usage of non-contact vital sign monitoring systems make it possible to monitor the patient unobtrusively, solving the abovementioned problem. This can be achieved by installing such a system in the patient's bed, regardless of location - in the hospital or home (even using a regular bed). In this way, this step ensures that indicators can be monitored anywhere [1]. One of the indicators that require such monitoring is respiratory rate. This is because its changes can indicate various severe medical conditions, including sleep medicine [2].

II. Related Works

Different invasive and non-invasive measurement methods can be used to obtain breath information [3-4]. A non-invasive measurement method, it is essential to note the existence of approaches using low-cost and non-contact multimodal sensor fusion, which extracts vital signs related to sleep from radar signals and sound-based context awareness techniques [5]. The various systems in which sensors are combined with the patient bed are also of particular interest. For example, an overview of health monitoring systems for use at the bedside can be found in [1]. Devices based on piezoelectric sensors can be highlighted [6]. In the meantime, Albuhari et al. in [7] presented a force sensor placed under the bed. An unobtrusive vital signs monitoring system used to assess sleep stages is shown in [8]. In addition, there is an accelerometer-based heart rate (HR) estimation system [9-10]. This system is also capable of estimating HR through the use of an accelerometer sensor. The same system is also capable of estimating RR [11].

Meanwhile, the authors of these works point out that the measurement results highly depend on the choice of sensor, the mechanical sensor holder, and its position. However, not all of these system parameters have been addressed. Thus, Conti et al. showed the choice of sensor for further studies [9]. More recently, the process of determining a specific system setup using a mechanical holder to obtain the most accurate measurement results has been presented [11]. However, determining the proper position of the sensor concerning the patient to improve measurement results has still not been given sufficient attention.

This work aims to determine the accelerometer sensor position related to the patient for a non-invasive respiratory rate measurement system using the particular system setup [11]. For this purpose, the patient's amplitude values of the respiratory signal at different sensor positions have been analyzed.

III. Methods

In summary, the system consists of the following parts: the mechanical holder, the sensor, and the computation unit with data storage possibility. All mentioned parts of the system are presented in the following subsections.

A. Mechanical holder

As noted earlier in the previous section, the measurement results are severely influenced by several aspects. One of these is the sensor holder because of its effect on the sensor's oscillation under the mattress. It is essential to ensure that the

[1] HTWG Konstanz, Alfred-Wachtel-Str. 8, 78462 Konstanz, Germany
{andrei.boiko,ralf.seepold}@htwg-konstanz.de,
[2] Reutlingen University, Alteburgstr. 150, 72762 Reutlingen, Germany
natividad.martinez@reutlingen-university.de

sensor is attached to the hanger; therefore, constant contact between the mattress and the sensor. In this paper, the mechanical holder (presented in Figure 1) is used to fix the sensor.

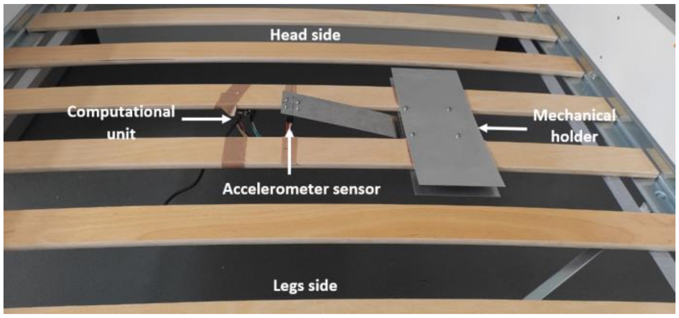

Fig. 1. The mechanical holder for the non-invasive RR measurement system.

The holder has a special adjustment for plate hanger length and thickness in order to obtain acceptable results [11].

B. Data acquisition

The system block associated with the signal acquisition should consist of a computing unit transmitting the data to the cloud or server, a storage module for data backup, and a sensor.

The ESP32 module has been selected as the computing unit in this work. This is because this unit is sufficient for data collection from the sensor. This device can support voltages up to 5V according to its technical characteristics. It also fulfills the cost requirements. The ESP32 module sends data to the PC via WiFi using the access point. In addition, a micro-SD module connected to the ESP32 allows each new entry to be locally stored as a backup in case the WiFi connection fails while sending data to the PC.

The ADXL355 accelerometer (Analog Devices) was used due to its good performance ratio between cost and accuracy of data acquisition. Its main features are low noise density, high sensitivity, and programmable digital high and low pass filters. Previously, this sensor has been applied successfully in non-invasive cardiac signal-sensing systems [12].

C. Signal processing

The signal processing for RR estimation was implemented in MATLAB. In the first step, the raw data from the ADXL355 (breathing signal) was divided into windows corresponding to the subject's position on the bed at time points according to the experiment protocol. The average breathing amplitude was then estimated for each window and subtracted to compensate for the sensor's gravitational acceleration effect and possible non-ideal positioning. A bandpass and moving average filter were then applied to the signals, with the moving window applied twice to minimize the error of detecting false breath peaks. For the bandpass filter, a frequency range of [0.05; 0.5]Hz has been chosen, sufficient to analyze human breathing at rest. Finally, the average respiratory signal amplitude excursion values for each window and patient position were calculated. The maximum difference between the calculated respiratory amplitude values was estimated to determine the preferred relative sensor position for RR estimation.

D. Experiment design

An experiment was performed to identify the most appropriate sensor position related to the patient to detect respiratory rate. In the beginning, the ADXL355 was placed under the bed mattress. The motion sensor was positioned in the bed center at chest level during the experiment. Then positions approximately corresponding to the level of the xiphoid process (solar plexus), diaphragm, and abdominal muscles were used to acquire data from other sensor positions (see Figure 2).

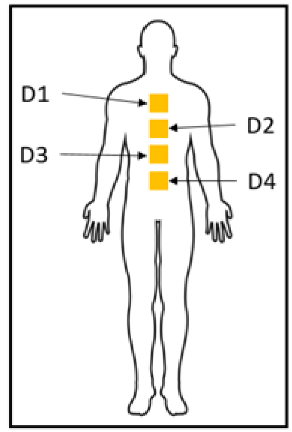

Fig. 2. The scheme of considering sensor distribution.

The sampling rate has been set at 31Hz, sufficient for the breathing signal bandwidth. In the beginning, the subject was asked to lie on the bed in a prone position (i.e., abdominal position), then the measurement was started. In order to record one series of measurements, the subject had to lie for 5.5 minutes in a relaxed state. The subject was also required to change one's body position on the bed in the following sequence: prone position, right side, backside, and left side every 80 seconds. It is important to note that the time window's first and last 10 seconds were removed from the 80-second window during the signal processing phase. One of the reasons is to stabilize the sensor position using a holder mounted under the bed when the person is already lying on the bed. It is also important to achieve a relaxed patient state in the first seconds of the experiment and then obtain data. Thus, a time interval of 60 seconds was estimated for each patient's position. In the data processing phase, this interval would be divided into 30-second epochs for analysis. In addition, this measurement series duration (5.5 minutes) is due to the need to wait a few seconds after all necessary procedures during one series before finishing data recording. After each recorded series of measurements, the position of the transducer was changed according to the order presented above. For this, the patient had to get out of bed. This was also due to avoiding the same patient position during measurements. Moreover, this approach provides more precise data for further evaluation of the sensor position. One series of measurements was performed for each holder set.

IV. RESULTS

The result of this initial research is a definition of accelerometric sensor position that allows us to get acceptable measurement results of respiratory signals from patients. Figure 3 shows typical acceleration signals from one subject's position and one of the considered sensor distributions.

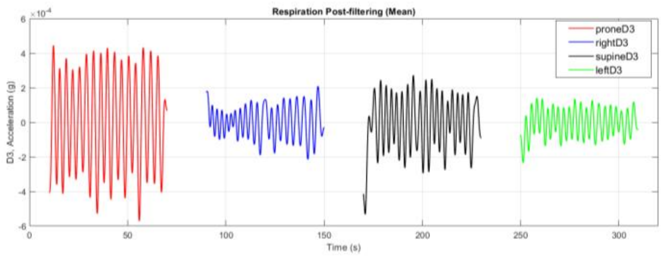

Fig. 3. Example of extracting signal.

In order to determine a proper sensor position concerning the patient, it is important to evaluate the average acceleration amplitude excursion that corresponds to the respiratory signal. The data were collected from 5 subjects (four men and one woman) who participated in the experiment. It is important to note that all subjects had approximately the same body composition. Thus, the amplitude excursion values were calculated from 10 30-second windows for each patient subject position. Table 1 shows the results for normal patient breathing in all considering bode positions and sensor distributions.

TABLE I. AVERAGE ACCELERATION AMPLITUDE EXCURSION

Sensor distribution	**Subject position**			
	Prone	**Right**	**Supine**	**Left**
	Average acceleration amplitude excursion [10^{-4}, m/s^2]			
D1	3.032	1.034	1.317	0.743
D2	3.420	1.157	1.693	1.216
D3	2.384	1.286	2.978	1.368
D4	4.569	1.119	0.879	0.662

The sensor distributions D2 and D3, which correspond to xiphoid process and diaphragm, allow getting the maximal value of considering parameter (average amplitude excursion) based on the presented results. However, it is important to carry out additional measurements and evaluation results to determine the best of these distributions.

V. Conclusion and Future Work

The study determined the preferred position of the accelerometer sensor about the patient for a non-invasive respiratory rate measurement system. Meanwhile, the evaluation of respiratory signals is challenging due to the strong influence of ambient noise. As mentioned earlier, among the factors affecting signal quality are the mechanical design and position of the sensor under the mattress and the minimum number of sensors to achieve high system accuracy.

The mean acceleration values of the amplitude of regular and deep breathing signals were analyzed to determine the proper position of an accelerometer sensor for monitoring the patient respiratory rate. Based on the results, it was determined that the position which corresponds to xiphoid process and diaphragm was the preferred position among those considered in this initial study for further work with the system used in this paper.

Despite many advantages, such as the simple design combined with efficient hardware and unobtrusive measurement capability, the system in question and the study as a whole still has enormous potential for improvement.

For example, more subjects need to be included in the study, which would give a more accurate and complete picture of the measurement results. Equally important is the validation of the results obtained using registered and recognized vital sign monitoring systems (e.g., polysomnography), which would significantly improve the results' quality. Also, no consideration has been given to reviewing and obtaining data from other perspectives. This can be achieved by shifting the sensor some distance away from one or more considered positions. In addition, there is also potential for a signal processing algorithm. One of the possible ways, for example, is to consider the system for heart rate and sleep apnea detection. In other words, there is a need for future research to improve the system, as this research is at an initial stage.

VI. Acknowledgment

This research was partially funded by (a) Carl Zeiss Foundation and the MORPHEUS-Project "Non-invasive system for measuring parameters relevant to sleep quality" (project number: P2019-03-003); and (b) by the German Academic Exchange Service – DAAD within the project "Portable system for detecting and alerting driver fatigue" supported (project number 57562477).

VII. References

1. Conti, M., Orcioni, S., N. Martínez Madrid, Gaiduk, M., Seepold, R., "A Review of Health Monitoring Systems Using Sensors on Bed or Cushion" in Lecture Notes in Computer Science, vol. 10814 LNBI, 2018, pp. 347–358, doi: https://doi.org/10.1007/978-3-319-78759-6_32
2. Zhang, X., Mohamed Kassem, M.A., Zhou, Y., Shabsigh, M., Wang, Q., Xu, X., "A Brief Review of Non-invasive Monitoring of Respiratory Condition for Extubated Patients with or at Risk for Obstructive Sleep Apnea after Surgery" Frontiers in medicine vol. 4 26. 8 Mar. 2017, doi:10.3389/fmed.2017.00026
3. Fan, D., Ren, A., Zhao, N., Haider, D., Yang, X. and Tian, J., "Small-Scale Perception in Medical Body Area Networks" in IEEE Journal of Translational Engineering in Health and Medicine, vol. 7, pp. 1-11, 2019, Art no. 2700211, doi: 10.1109/JTEHM.2019.2951670
4. Tomita, K., Nakada, Ta., Oshima, T., Oami, T., Aizimu, T., Oda, S., "Non-invasive monitoring using photoplethysmography technology" J Clin Monit Comput 33, 637–645 2019. https://doi.org/10.1007/s10877-018-0205-5
5. Chung, K., Song, K., Shinet, K., "Noncontact Sleep Study by Multi-Modal Sensor Fusion," Sensors, vol. 17, no. 7, p. 1685, Jul. 2017.
6. Tal, A. et al. "Validation of Contact-Free Sleep Monitoring Device with Comparison to Polysomnography." JCSM, vol. 13,3 517-522, 2017.
7. Albukhari, A., Lima, F., Mescheder, U., "Bed-embedded heart and respiration rates detection by longitudinal ballistocardiography and pattern recognition" Sensors , 19(6). 2019, doi: 10.3390/s19061451
8. Gaiduk, M., Wehrle, D., Seepold, R., Ortega, J.A., "Non-obtrusive system for overnight respiration and heartbeat tracking" Procedia Computer Science 176 (2020): 2746-2755, doi: https://doi.org/10.1016/j.procs.2020.09.282

9. Conti, M., Aironi, C., Orcioni, S., Seepold, R., Gaiduk, M. and N. Martínez Madrid, "Heart rate detection with accelerometric sensors under the mattress" 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), 2020, pp. 4063-4066, doi: 10.1109/EMBC44109.2020.9175735
10. Shkilniuk, Y., Gaiduk, M., Seepold, R., "Unobtrusive Accelerometer-Based Heart Rate Detection" 2021. In: Saponara, S., De Gloria, A. (eds) Applications in Electronics Pervading Industry, Environment and Society. ApplePies 2020. Lecture Notes in Electrical Engineering, vol 738. Springer, Cham. https://doi.org/10.1007/978-3-030-66729-0_6
11. Boiko, A., Scherz, W.D., Gaiduk, M., Gentili, A., Conti, M., Orcioni, S., Seepold, R., N. Martínez Madrid, "Sleep respiration rate detection using an accelerometer sensor with special holder setup" 2022 IEEE International Conference on e-Health and Bioengineering (EHB), 2022. *Accepted to publish*.
12. Mora, N., Cocconcelli, F., Matrella, G. and Ciampolini, P., "Accurate Heartbeat Detection on Ballistocardiogram Accelerometric Traces" in IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 11, pp. 9000-9009, Nov. 2020, doi: 10.1109/TIM.2020.2998644