A SmartBed for Non-obtrusive Physiological Monitoring During Sleep: The LAID Project

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A SmartBed for Non-obtrusive Physiological Monitoring During Sleep: The LAID Project

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Abstract. The individual experience of inadequate or insufficient sleep is one of the most common health issues in the industrialized world. The 65% of Italian population reports disturbed sleep experiences, while chronic sleep disorders affect about 10% of the population. The people with inadequate and unsatisfactory sleep often suffers drowsiness during the day associated with both somatic and mental disorders. For these reasons, the systematic and continuative monitoring of sleep is one of the main objectives in preventive, personalized and participatory sleep medicine. The purpose of this paper is to describe the architecture of a "smart mattress" (SmartBed) that is the main outcome of the Italian R&D project called LAID. SmartBed will be able to non-obtrusively collect physiological and environmental parameters and signals, to processing them and to provide information about the quality of sleep, the levels of stress, and more generally the well-being of an individual. Specifically, SmartBed will be able to estimate data relating to cardiorespiratory activity, movements, body position, snoring and environmental parameters. SmartBed aims to obtain a continuative and ecological assessment of sleep and well-being of a person, in order to improve his quality of life. SmartBed will be a fundamental tool for carrying out both longitudinal and epidemiological studies on the quality of sleep and life on general population.

Keywords: Sleep · Sensorized mattress · Non-obtrusive sensors

1 Introduction

The inadequate sleep and insomnia are the most common human health issues in the industrialized societies. As the experiences during the day deeply influences sleep quality, sleep also influences the efficiency of activities during wakefulness. In fact, insomnia correlates with high rates of absenteeism from work, with the reduction of performance capabilities, and with accidents at work or on the road. Sleepless people have more frequent medical issues, indeed they use healthcare facilities and drugs much more

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than non-sleepless. Among the health problems related to insomnia the best known are metabolic diseases (diabetes and dyslipidemia), some cardiovascular diseases (myocardial infarction and hypertension), as well as cognitive impairment [1]. In addition, chronic insomnia increases the probability of death due to myocardial infarction as well as the vulnerability to affective psychopathology (Depression and Anxiety Disorders) [2]. In order to obtain a new tool to identify sleep disorders in the general population, we conceived an R&D project called **LAID** "Linking Automation to artificial Intelligence for revealing sleep Dysfunctions". LAID project aims to develop an innovative smart mattress (**SmartBed**) able to identify insomnia or preclinical sleep disorders early, with the final goals of reducing the socio-economic cost due to sleep disorders and increasing individual well-being condition. More specifically, LAID project is concern about the research and development of: i) a sensorized smart mattress for non-obtrusive physiological data collecting, ii) an innovative algorithms for physiological data processing and iii) a software for extraction of sleep quality index. With respect to previous developed smart mattress (e.g. [3]), LAID project aimed to obtain a low-cost product, with multi-sensors integration and innovative algorithm for sleep quality estimation.

2 Materials and Methods

2.1 Overall Architecture

In order to estimate the global quality of sleep, it is important to evaluate not only the physiological state of the subject but also the environmental conditions. Besides, it will also possible to associate sleep issues with both physiological alterations and specific features of environment where the subject sleeps.

The overall architecture of SmartBed is composed by the following functional blocks (see Fig. 1):

- Physiological data collector (PDC)
- Environmental data collector (EDC)
- Docking station (DS)

Both PDC and EDC are wired to DS via serial communication interface. The DS of the first prototype is windows 10 based system with a tailored software for managing PDS and EDC, processing the signals and parameters from PDS/EDC, storing the collected data, and finally extracting the sleep quality and well-being indices. The future version of DS will be managed also by a user-friendly interface by mobile device and the data will be sent and stored on specific cloud database.

The most innovative aspects of SmartBed is the PDC and the integration between PDC/EDC data. PDC is made of a custom designed acquisition unit and it has two kind of sensors: three-axial accelerometers and a pressure matrix. The mattress of SmartBed is made by Materassificio Montalese S.P.A. (Pistoia, Italy), the PDC is design and develop by EB Neuro S.P.A (Firenze, Italy), EDC and DS by BP Engineering S.P.A. (Carrara, Italy).

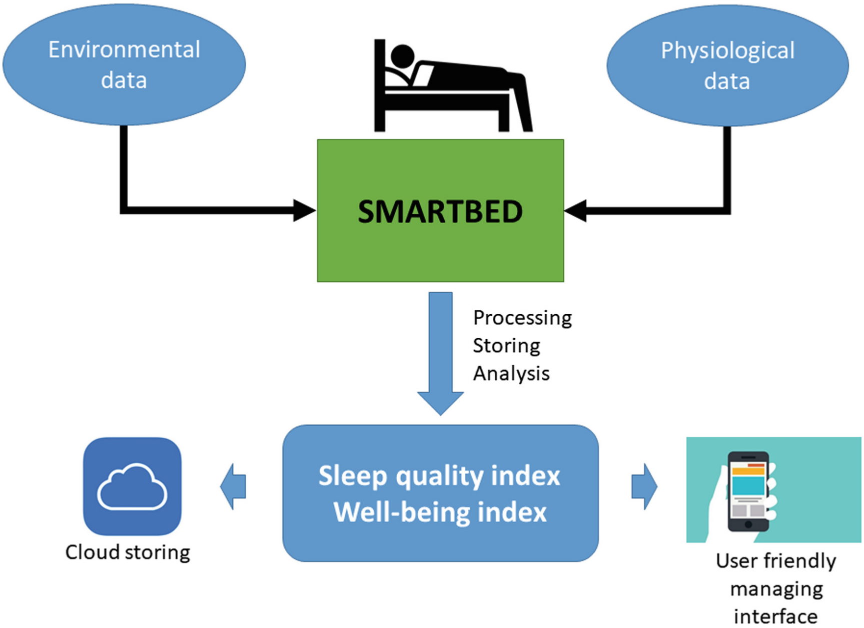

Fig. 1. Overall architecture of SmartBed.

2.2 Accelerometers

The accelerometric signals collected by SmartBed will be used to evaluate the cardiac and respiratory activities and movements of the subject during the night in a non-obtrusive way. The used accelerometers are the PNADXL362 (Analog Device), their specifications are reported in Table 1.

Table 1. Accelerometer specifications

Number of axes	3
Range	± 2 g
Supply voltage	3.3 V
Sensitivity	1 mg/LSB
Raw data noise level	175 $\mu g/\sqrt{Hz}$ (ultralow noise mode)
Bit resolution	12 bits
Sampling frequency	128 Hz
Shape and dimension	Circular, diameter 2.2 cm

We used three accelerometers simultaneously but in different positions of the mattress. One was placed in a central area of the mattress, and the other two in lateral and contro-lateral sites (as shown in Fig. 2). In this way, by mediating the signals from different accelerometers we can reduce the noise. Furthermore, if the subject places itself on non-centered positions our idea is to select or set a higher weight to the accelerometer closer to the subject. Indeed, we can obtain the exact body position of the subject on the mattress by using the pressure matrix.

The accelerations collected from PDC are used to estimate the movements, the cardiac and respiratory activities of the subjects on SmartBed during the night.

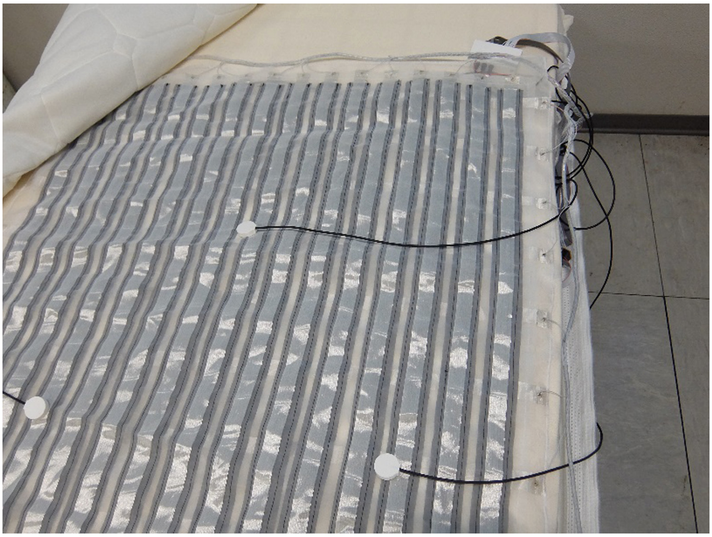

Fig. 2. Position of accelerometers (white dots) over the pressure matrix.

2.3 Pressure Matrix

Starting from the analysis of the literature and considering the lower complexity, the lower cost and the greater tolerance to external disturbances, we have considered the resistive sensor matrix solution, similar to the one reported in [4]. Considering the project specifications (spatial resolution <10 cm, single mattress measuring 190×90 cm), we have built a mattress cover based on a resistive matrix of 15×13 uniformly spaced sensing areas that cover a surface of 125×75 cm (i.e. head and feet will not be considered in this first version of the prototype). Figure 3 shows a schematic description of the proposed solution: the central layer is a pressure sensing semi-conductive fabric while the additional two layers are fabrics with integrated row and column conductors (note that row and column conductors are perpendicular).

Two analog multiplexers are used to scan rows (row mux) and columns (column mux) in order to select all the sensing areas of the resistive matrix. The row mux sequentially connects each row conductor to Vcc (3.3 V) through a pull-up resistor R1 (2 KΩ). When a row is selected (i.e. powered), the col mux sequentially connects each col conductor

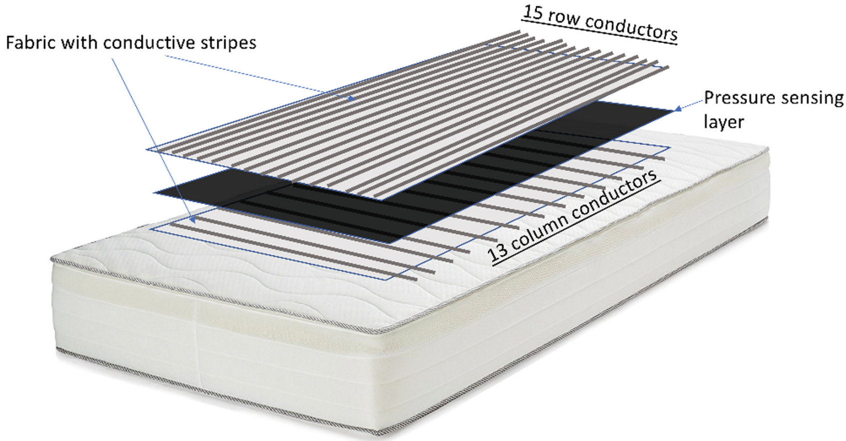

Fig. 3. Proposed solution: mattress cover based on a resistive matrix with 13 column conductors and 15 row conductors for a total of 195 sensing areas.

to a voltage divider stage (pull down resistor R2, 10 KΩ). In this way, each crossing between a row and a column represents a sensing area whose electrical resistance will decrease as the applied pressure increases.

For the pressure-sensing layer, we have used the semi-conductive fabric CARBOTEX 03-82 by SEFAR AG. The top and bottom layers are made of a PET fabric (from SEFAR AG) with integrated evenly spaced metallic stripes. According to our indications, the metallic stripes have 2 cm width and are separated 3 cm in the top layer and 8 cm in the bottom layer. As described in [5], this sensing architecture has parasitic resistivity on the transversal directions due to the conductivity of the pressure-sensing layer. To reduce the cross-talk due to the parasitic resistivity we have built our prototype by additionally cutting the sensing layer in stripes parallel to the column direction (around 3.5 cm width). The stripes were then sewn to the top layer to be centered with respect to the row conductors. Figure 4 reports the details of the pressure sensing matrix prototype.

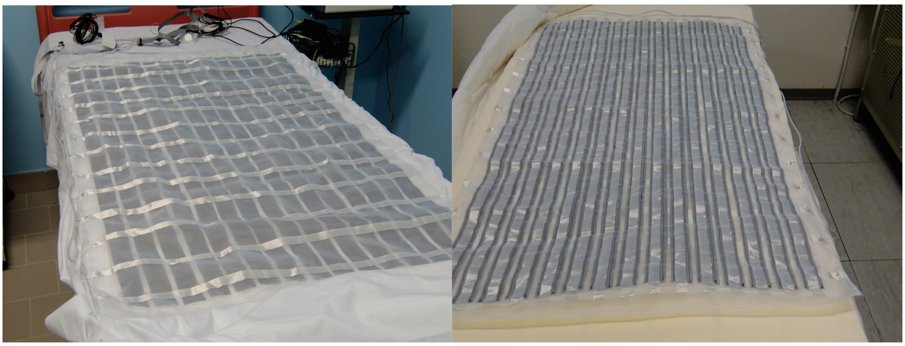

Fig. 4. Pressure sensing matrix: on the left the top layer, on the right the bottom layer.

2.4 Environmental Data

As expected, environmental acoustic noise also influences sleep [6–9]. Ohrstrom [7] has shown that intermittent acoustic noise causes a worsening of sleep with respect to constant levels of noise. In a report prepared for the World Health Organization in 1995, Berglund and Lindvall [11] recommend a continuous noise level no higher than 30/35 dB indoors and a maximum of 45 dB for intermittent noise exposure caused by single noisy events. Several studies have shown that sleep is influenced by both environmental temperature and humidity [9, 12, 13].

The comfortable range of temperature for a human is between 22.8 °C and 26.1 °C in summer and between 20 °C and 23.9 °C in winter. High humidity is not suited to higher temperatures than to lower temperatures (e.g. relative humidity of 60% at 26.1 °C and 85% at 20 °C are both optimal) [10]. In addition, exposure to light can alter sleep, through the inhibition of melatonin secretion in humans.

Therefore, all these studies have shown that is extremely important to monitor and evaluate environmental conditions in order to assess the quality of sleep and overall well-being.

The EDC module is based on Seeeduino V4.2 board. It is composed by several sensors to collect the following environmental variables: i) sound intensity, ii) temperature, iii) relative humidity, iv) luminosity and v) atmospheric pressure. All the variables, except for the sound intensity, is collected with a sampling frequency of 1 Hz. Since the environmental sound intensity is the only parameter that has a potentially fast dynamic and it is also be used to evaluate the respiratory activity and snoring, its sampling frequency is set to 20 Hz. All the signals and parameters are collected synchronized with respect to the data from PDC.

2.5 Processing Algorithm

In the first prototype of SmartBed, the DS module is a windows 10 based system with a tailored software able to collect simultaneously all the signals from PDC and EDC. The software on DS on the next prototype of SmartBed will also contain the processing algorithm to estimate the sleep quality index that is now in a preliminary version. The sleep quality index will be mainly obtained from the integration of two kind of information: macrostructure of sleep (sleep stages, sleep duration and sleep apnea episodes) and environmental condition. The macrostructure of sleep will be estimates from the following parameters: the cardiac activity, the respiratory activity, the movements and the body position during the night. The cardiac activity (heart rate and heart rate variability) will be estimated from the ballistocardiogram obtained from the accelerometer signals and by using validated algorithms available in literature [14–16]. The respiratory activity (breathing rate) will be obtained from signals of accelerometers, pressure matrix and sound sensor [17–19]. The movements of the subject will be evaluated from the accelerometers and the pressure matrix. Finally, the body position will be assessed with pressure matrix (Fig. 5).

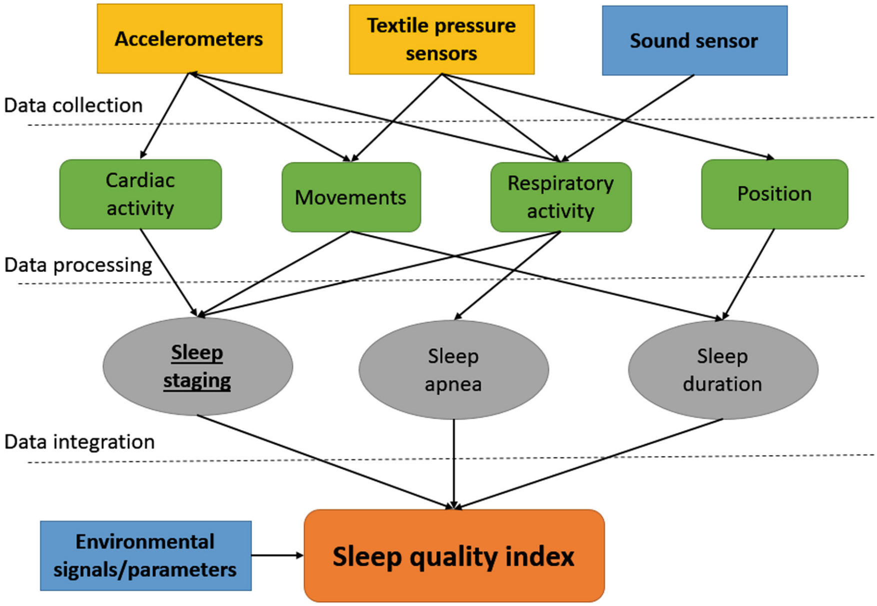

Fig. 5. Flow information and processing stages from sensors to sleep quality index.

3 Results

The actual prototype of SmartBed can acquire and store the data from both PDC and EDC. In Fig. 6 the signals (60 s) of each axis of the three accelerometers are reported during a recording of a subject laying on SmartBed.

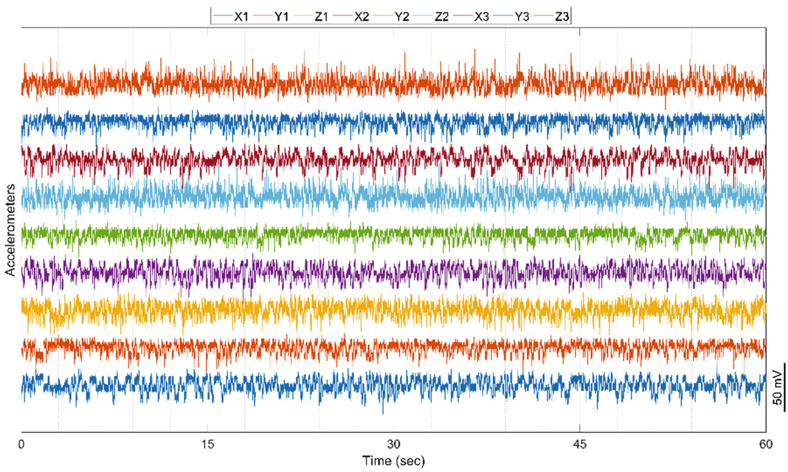

Fig. 6. Signals from the three 3-axial accelerometers of 60 s with a subject standing on SmartBed.

The accelerometers respond consistently to the accelerations to which they are subjected by the person on the mattress, it is possible to clearly detect the macroscopic movements by the subject on the mattress. The next step of the project will be dedicated to the evaluation of the quality of the signals for the estimation of indexes of the cardiac and respiratory activity.

Figure 7 reports the processed output of the pressure-sensing matrix when a subject is lying on the mattress in two different positions (i.e. center of the mattress and towards his right). The chest, the upper arms and the legs can be easily recognizable. The image reported in the figure is obtained by a linear interpolation of the raw output values in each sensing area. In addition, a threshold algorithm is applied to compensate for the sensor bias.

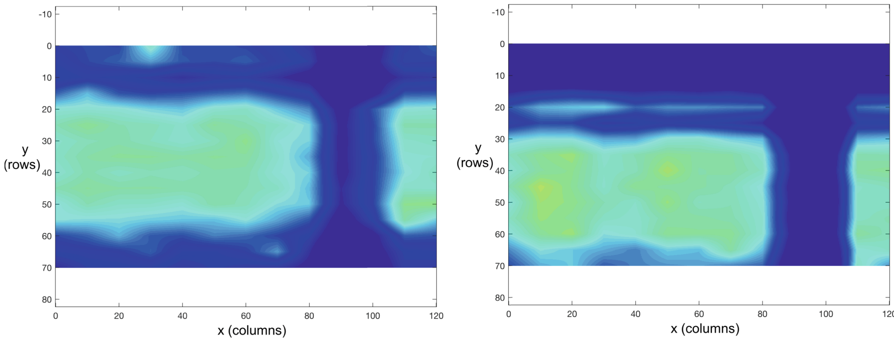

Fig. 7. Pressure maps with same subject in two different positions on the mattress (on the left the subject is centered on the mattress, while on the right the subject has moved to his right).

4 Conclusion

Years of scientific evidence have reported the importance of the sleep that is strictly related to our psychophysical wellbeing, the stability of our mood, our memories and cognitive abilities, and to the quality of our health. It is also well known that sleep alterations can completely modulate homeostatic condition and adaptive functions of subjects during the day.

The main aim of LAID project will be the design and development of a "smart mattress" (SmartBed) able to record vital and environmental signals/parameters in a non-obtrusive way, to analyze them and to provide information about the quality of sleep and more generally about the well-being and on quality of life of an individual.

The first stage of the LAID project is concluded and now the first hardware and software prototype of SmartBed is available and well-working.

In conclusion, the first prototype of SmartBed has good performances regarding the acquisition of measures related to the physiology of the subject on the sensorized mattress and the environmental parameters. At now, the signals and parameters collected that can be collected are: i) 3-axial accelerations, ii) pressure matrix, iii) environmental parameters (noise, temperature, relative humidity, atmospheric pressure and luminosity). Future activities will be aimed at integrating the signals and testing the system with an adequate number of subjects.

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References

1. Terzano, M.G., et al.: Studio Morfeo: insomnia in primary care, a survey conducted on the Italian population. Sleep Med. **5**(1), 67–75 (2004)
2. Leger, D., Guilleminault, C., Bader, G., Levy, E., Paillard, M.: Medical and socio-professional impact of insomnia. Sleep **25**(6), 625–629 (2002)
3. Hao, J., Jayachandran, M., Kng, P.L., Foo, S.F., Aung, P.W.A., Cai, Z.: FBG-based smart bed system for healthcare applications. Front. Optoelectron. China **3**(1), 78–83 (2010). https://doi.org/10.1007/s12200-009-0066-0
4. Cheng, J., Sundholm, M., Zhou, B., Hirsch, M., Lukowicz, P.: Smart-surface: large scale textile pressure sensors arrays for activity recognition. Pervasive Mob. Comput. **30**, 97–112 (2016)
5. Zhou, B., Lukowicz, P.: Textile pressure force mapping. In: Schneegass, S., Amft, O. (eds.) Smart Textiles, pp. 31–47. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-50124-6_3
6. Marquis-Favre, C., Premat, E., Aubree, D.: Noise and its effects - a review on qualitative aspects of sound. Part II: noise and annoyance. Acta Acustica United Acustica **91**(4), 626–642 (2005)
7. Ohrstrom, E., Skanberg, A.: Sleep disturbances from road traffic and ventilation noise - laboratory and field experiments. J. Sound Vib. **271**(1–2), 279–296 (2004)
8. Bonnet, M.H., Arand, D.L.: The impact of music upon sleep tendency as measured by the multiple sleep latency test and maintenance of wakefulness test. Physiol. Behav. **71**(5), 485–492 (2000)
9. Okamoto-Mizuno, K., Tsuzuki, K., Mizuno, K., Iwaki, T.: Effects of partial humid heat exposure during different segments of sleep on human sleep stages and body temperature. Physiol. Behav. **83**(5), 759–765 (2005)
10. Wickens, K., et al.: The determinants of dust mite allergen and its relationship to the prevalence of symptoms of asthma in the Asia-Pacific region. Pediatr. Allergy Immunol. **15**(1), 55–61 (2004)
11. Berglund, B., Lindvall, T.: Community noise: Center for Sensory Research. Stockholm University and Karolinska Institute (1995)
12. Libert, J.P., Dinisi, J., Fukuda, H., Muzet, A., Ehrhart, J., Amoros, C.: Effect of continuous heat exposure on sleep stages in humans. Sleep **11**(2), 195–209 (1988)
13. Dewasmes, G., Telliez, F., Muzet, A.: Effects of a nocturnal environment perceived as warm on subsequent daytime sleep in humans. Sleep **23**(3), 409–413 (2000)
14. Vehkaoja, A., Rajala, S., Kumpulainen, P., Lekkala, J.: Correlation approach for the detection of the heartbeat intervals using force sensors placed under the bed posts. J. Med. Eng. Technol. **37**(5), 327–333 (2013)
15. Brueser, C., Winter, S., Leonhardt, S.: Robust inter-beat interval estimation in cardiac vibration signals. Physiol. Meas. **34**(2), 123–138 (2013)

16. Choe, S.-T., Cho, W.-D.: Simplified real-time heartbeat detection in ballistocardiography using a dispersion-maximum method. Biomed. Res. India **28**(9), 3974–3985 (2017)
17. Sanchez Morillo, D., Rojas Ojeda, J.L., Crespo Foix, L.F., Leon Jimenez, A.: An accelerometer-based device for sleep apnea screening. IEEE Trans. Inf. Technol. Biomed. **14**(2), 491–499 (2010)
18. Nam, Y., Kim, Y., Lee, J.: Sleep monitoring based on a tri-axial accelerometer and a pressure Sensor. Sensors. **16**(5), 750 (2016)
19. Ren, Y., Wang, C., Yang, J., Chen, Y.: IEEE fine-grained sleep monitoring: hearing your breathing with smartphones. In: 2015 IEEE Conference on Computer Communications (Infocom) (2015)