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MEASUREMENT OF RESPIRATION AND HEARTBEAT USING A FLEXIBLE TACTILE SENSOR SHEET ON A BED

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ABSTRACT

We describe a measurement method of respiration and heartbeat using a Smart Rubber sensor, a rubber-based flexible tactile sensor sheet that we developed. This method is useful for unconstrained recording of a person sleeping soundly, sleeping lightly, lying down, sitting on a bed, and so on. Our goal is to monitor those who require nursing care. The proposed method measures respiration and heartbeat as follows. First, we measure body pressure by using the Smart Rubber sensor placed on a bed. Then, the method applies a frequency analysis to the time series data of body pressure. Finally, respiration and heartbeat are obtained by extracting suitable frequency bands. In the experiments, we show that respiration and heartbeat are successfully measured.

KEY WORDS

Monitoring, Respiration, Heartbeat, Unconstrained measurement, Tactile, Rubber-based flexible sensor sheet.

1 Introduction

In Japan, the percentage of people aged 65 or older against the total population is expected to increase to 29% in 2020, become 32% in 2030, and surpass 36% in 2040 [1, 2]. The percentage was approximately 23% in 2010. The number of those who require nursing care is increasing with this rapidly growing elderly population. The number of elderly people was estimated to be 4,802,000 in 2010 and is expected to increase to 6,440,000 in 2020 [3]. However, the nursing care industry is chronically understaffed. With the rapidly aging and shrinking population, Japan will face a more serious shortage of nursing staff in the near future. Therefore, the need to introduce nursing-care robots is now increasing to reduce the burden on caregivers.

The Ministry of Economy, Trade and Industry and the Ministry of Health, Labor and Welfare are promoting the development, commercialization, and introduction of robotic devices for nursing care in the following five priority areas: transfer care, movement assistance, toilet care, observation care, and bathing care [4]. The area of observation care includes monitoring system platforms consisting of devices with sensors and external communication functions using robot technology. For example, sleep monitoring gives useful information for maintaining good health and detecting diseases.

Polysomnography (PSG) [5] is the major diagnostic means for sleep disorders. A polysomnogram records the biophysiological changes of many body functions that occur during sleep, such as brain activity (electroencephalograms), heart activity (electrocardiograms), eye movements, muscle activity (electromyograms) of the chin, and respiratory airflow. The PSG is capable of accurately determining sleep stage. However, the PSG interferes with natural sleep because of the numerous sensors attached to the body of a patient. If it is to be used in daily life, the monitoring system should be almost unnoticed by the monitored person.

The sleep stage is estimated by using easily measured body functions including respiration rate, heart rate, and body movement intervals during sleep [6–9]. Watanabe *et al.* developed a noninvasive and unrestrained algorithm for estimating the sleep stage by using heartbeat and body movement [6], which were measured via a pneumatic method on an air mattress [10]. Kambayashi *et al.* estimated the depth of sleep by using body movement measured by a passive infrared type motion sensor [7]. Okada *et al.* developed a non-restrictive and non-invasive sleep evaluation method using body movement detected from a recorded video during sleep [8]. Harper *et al.* examined the potential to classify sleep and waking states over the first six months of life in normal infants by using only cardiac and respiratory measurements [9].

This paper proposes a method for unconstrained measurement of respiration and heartbeat of a person lying on a flexible tactile sensor sheet. The method can measure respiration and heartbeat based on the body pressure measured by the tactile sensor. The sleep stage is obtained by analyzing respiration and heartbeat.

Many methods for unconstrained measurement of respiration and/or heartbeat have been presented in the past several decades [11]. However, these methods do not obtain pressure distribution patterns and cannot distinguish lying postures of a person on a bed. Therefore, when two or more people, or a person with a pet, are on a bed, their pressure changes mix and cannot be measured separately. In addition, the information of the lying postures is also useful for detecting a sleep condition and diagnosing disorders, including sleep apnea syndrome and bedsores [12]. In one study [13], pressure distribution patterns and respi-

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ration were measured by many pressure sensors attached on a bed, but heartbeat was not measured. Moreover, each method has individual problems: air-sealed mattresses are not sufficiently thin because they are several centimeters thick, observation cameras would cause an invasion of a monitored person's privacy, and other devices are relatively expensive and setting them is not easy. We can easily measure not only respiration and heartbeat but also lying postures by using the tactile sensor sheet.

The remainder of the paper is organized as follows. Section II explains the measurement method of respiration and heartbeat. The tactile sensor to measure the body pressure is described in Section III. Section IV describes experiments for measuring respiration and heartbeat in three lying positions of a male subject: lying on his back, lying on his stomach, and lying on his side. Conclusions of the present study and future work are presented in Section V.

2 Measurement Method of Respiration and Heartbeat

We propose a measurement method of respiration and heartbeat by using a flexible tactile sensor sheet. As shown in Figure 1, the proposed method measures respiration and heartbeat. First, we measure body pressure at the chest by using a tactile sensor sheet placed on a bed. Then, the method applies a frequency analysis to the time series data of the body pressure. Finally, respiration and heartbeat are obtained by extracting suitable frequency bands.

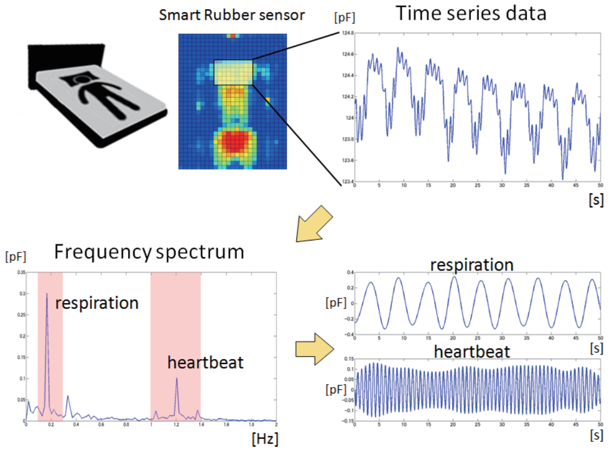

Figure 1. Measurement method of respiration and heartbeat using a flexible tactile sensor sheet.

We assume that a monitored person stays relaxed in a bed. Hence, violent body movements rarely occur. Therefore, we can measure respiration and heartbeat in most cases. Although an overlap in the frequency bands for respiration and heartbeat might occur under extreme clinical conditions, then we can know the occurrence of an emergency by the disappearance of the two peaks originating from respiration and heartbeat.

2.1 Frequency analysis applied to the time series data of the body pressure

The method applies a frequency analysis to the time series data of the body pressure for measuring respiration and heartbeat. We measure the body pressure by using a tactile sensor sheet placed on a bed. We employ a fast Fourier transform (FFT) [14, 15] for this frequency analysis.

When a human inhales, the chest gets bigger. Also, the change in body pressure by the heartbeat is bigger when the measurement area is located closer to the heart. Therefore, we use the body pressure measured at the chest.

2.2 Extracting suitable frequency bands for respiration and heartbeat

When a human stays relaxed in a bed, his/her respiration and heartbeat have an almost constant cycle. Therefore, the proposed method can measure respiration and heartbeat by extracting suitable frequency bands. A respiratory waveform and a heartbeat waveform are obtained by putting back the extracted signals in the frequency ranges into signals in the time ranges.

3 Device for Measuring Body Pressure

To implement our method, we measure the body pressure applied to a bed by the weight of a person lying on it. We use a Smart Rubber (SR) sensor [16] (Tokai Rubber Industries, Ltd.) as an input device for measuring the body pressure. The SR sensor is a rubber-based flexible tactile sensor sheet that we developed. All components of the SR sensor, including the wires, are made of only rubber-based materials. Thus, the SR sensor is soft, flexible, and thin, and does not cause discomfort to the person lying on it. The use of the SR sensor makes it possible to measure the body pressure noninvasively and without constraint.

The structure of the SR sensor is shown in Figure 2. The SR sensor, which uses electric capacitance to measure pressure, is a three-layered structure consisting of a dielectric layer sandwiched between two electrode layers. Each electrode layer has a number of parallel ribbon-like electrodes. The electrodes in the two layers are oriented orthogonally to each other so that independent capacitive sensor cells are formed by the intersection of the two orthogonal layers. When the numbers of electrodes in the upper and lower layers are m and n, respectively, $m \times n$ capacitive sensor cells are formed on the sensor sheet.

When pressure is applied on the SR sensor, the dielectric layer deforms and the distance between the upper and lower electrodes becomes shorter. As a result, the capacitance of the cell increases. By scanning the capacitances of the cells in the SR sensor, we can detect the two-dimensional pressure distribution on the sensor sheet. Tactile sensors based on this principle were proposed years ago, and sensor sheets that employ metal electrodes are commercially available [17]. However, the high cost and/or

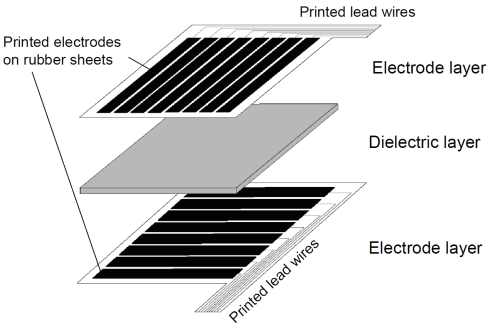

Figure 2. Schematic structure of Smart Rubber sensor.

the lack of flexibility are issues for their use in healthcare situations. We developed a soft and flexible SR sensor consisting of rubber parts that include the electrodes. The electrodes are made by printing, which keeps the fabrication cost low.

A photograph of the SR sensor used for our experiments is shown in Figure 3. The sensing part of this sensor has a square shape with each side measuring 478 [mm], and the thickness is 3.5 [mm]. The SR sensor is connected to a controller, which obtains the pressure distribution by scanning. Measuring one cell takes 184 [μs], which means 47 [ms] for the whole sensor sheet. The specifications of this sensor are shown in Table 1.

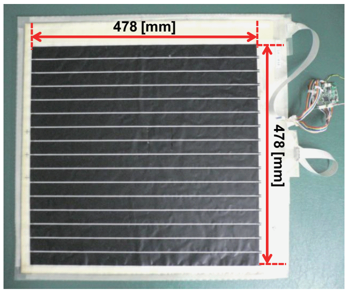

Figure 3. Photograph of the SR sensor.

Table 1. Specifications of the SR sensor

Number of cells	256	
	Length	Width
	16	16
Size of sensor sheet	478 [mm]	478 [mm]
Size of a sensor cell	28 [mm]	28 [mm]
Size of a gap between cells	2 [mm]	2 [mm]
Sampling rate	20 [Hz]	

4 Experiments

We applied our method to a subject lying on the SR sensor placed on a bed. The subject was male of age 30 years. We used the average value of the cells at the chest of the subject as the body pressure for measuring respiration and heartbeat.

We applied the method to three different postures of the subject: lying on his back (Figure 4(a)), lying on his stomach (Figure 4(b)), and lying on his side (Figure 4(c)). The extracted frequency bands were determined by referring to a preliminary experiment, as follows: (1) The extracted frequency band for the respiration is from 0.1 to 0.3 [Hz] (from 6 to 18 [times/min]). (2) The extracted frequency band for the heartbeat is from 1.0 to 1.5 [Hz] (from 60 to 90 [times/min]).

The noise of the SR sensor is a mix of discretization noise, thermal noise, the influence of parasitic capacitance, and so on. However, we can attain the S/N ratio needed for measuring respiration and heartbeat with reproducibility because the noise is sufficiently small.

(a) on his back (b) on his stomach (c) on his side

Figure 4. Photographs of the three postures.

For comparison, we measured respiration and heartbeat by using a respiratory sensor and a heartbeat sensor, respectively. Photographs of the respiratory sensor and the subject wearing the sensor are shown in Figure 5. The respiratory sensor measures the movement of the chest. The sampling rate of this sensor is 50 [Hz]. Photographs of the heartbeat sensor and the subject wearing the sensor are shown in Figure 6. The heartbeat sensor measures the subject's heartbeat in an electrocardiogram. The sampling rate of this sensor is 100 [Hz].

(a) (b)

Figure 5. Photographs of (a) the respiratory sensor and (b) the subject wearing the respiratory sensor.

4.1 Measurement results of respiration

The frequency spectrums of the three postures by applying FFT to the body pressure for measuring respiration are

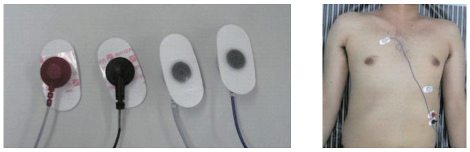
(a) (b)

Figure 6. Photographs of (a) the heartbeat sensor and (b) the subject wearing the heartbeat sensor.

shown in Figure 7. We used data obtained in 51.2 seconds (1024 data counts) because the FFT requires data whose size is a power of two. The Nyquist frequency is 10 [Hz] since the sampling rate is 20 [Hz]. The horizontal axes represent the frequency range from 0 to 2 [Hz], because each amplitude spectrum is approximately 0 in the frequency range over 2 [Hz]. Each result has a high peak in the respiratory frequency band (from 0.1 to 0.3 [Hz]).

The measurement results of respiration of the three postures are shown in Figure 8. The blue lines indicate the respiratory waveform obtained by putting the extracted respiratory signals in the frequency ranges into signals in the time ranges. The red lines indicate the output value of the respiratory sensor. Each respiratory waveform obtained by our method is similar to the output of the respiratory sensor.

4.2 Measurement results of heartbeat

We applied our method to the measurement of heartbeat in the same way described in Section 4.1. The frequency spectrums of the three postures by applying the FFT to the body pressure for measuring heartbeat are shown in Figure 9. Each result has a peak in the heartbeat frequency band (from 1.0 to 1.5 [Hz]). Moreover, the frequency spectrums by applying the FFT to the output of the heartbeat sensor are shown in Figure 10. The peak frequency in the heartbeat frequency band of each posture in Figure 9 agrees with the peak frequency in Figure 10.

The measurement results of heartbeat of the three postures are shown in Figure 11. The blue lines indicate the heartbeat waveform measured by our method, and the red lines indicate the output value of the heartbeat sensor. The period of the heartbeat waveform of each posture is almost equal to the period of a cardiac cycle measured by the heartbeat sensor. Thus, the heartbeat is successfully measured by our method.

5 Conclusion and Future Work

5.1 Conclusion

We developed a method for unconstrained measurement of respiration and heartbeat of a person lying on a flexible tactile sensor sheet. In the experiments, we applied our method to a subject in three different postures: lying on his back, lying on his stomach, and lying on his side. We successfully measured respiration and heartbeat in all three postures.

5.2 Future work

In future work, we will develop a decision method for the suitable measurement location of body pressure for the measurement of respiration and heartbeat. The signals originated from respiration and heartbeat are small compared with the load of the person's weight. In particular, heartbeat signals are faint. To measure them, we improve their S/N ratio by averaging oversampled data. However, the averaging process takes time and can be performed only at a limited number of locations on the sensor. Hence, a decision method for the suitable locations for measuring respiration and heartbeat is needed.

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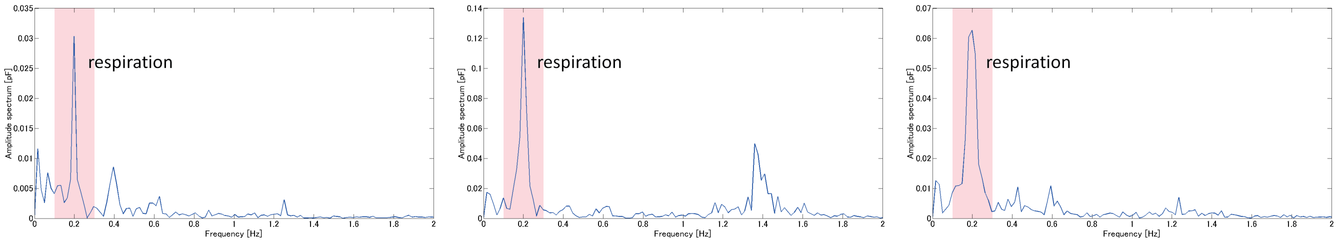
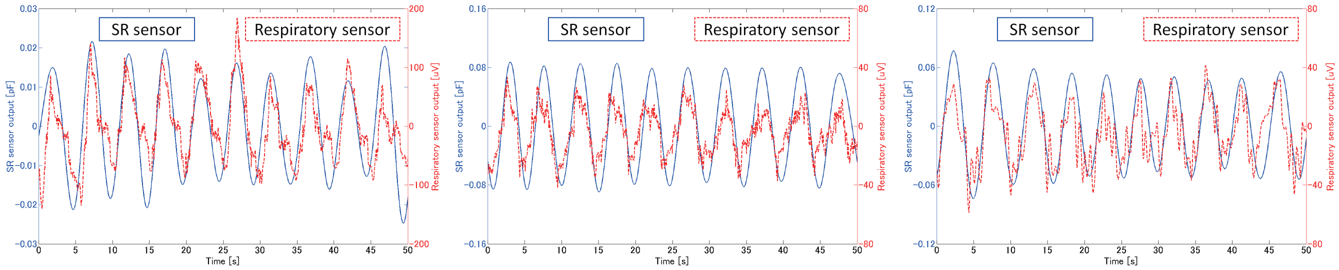


on his back on his stomach on his side

Figure 7. Frequency spectrums of the three postures by applying the FFT to the body pressure for measuring respiration. The three postures are lying on his back, on his stomach, and on his side. The horizontal axes represent the frequency range from 0 to 2 [Hz]. The vertical axes represent the amplitude spectrum.



on his back on his stomach on his side

Figure 8. Measurement results of respiration of the three postures. The blue lines indicate the respiratory waveform obtained by our method. The red lines indicate the output value of the respiratory sensor.

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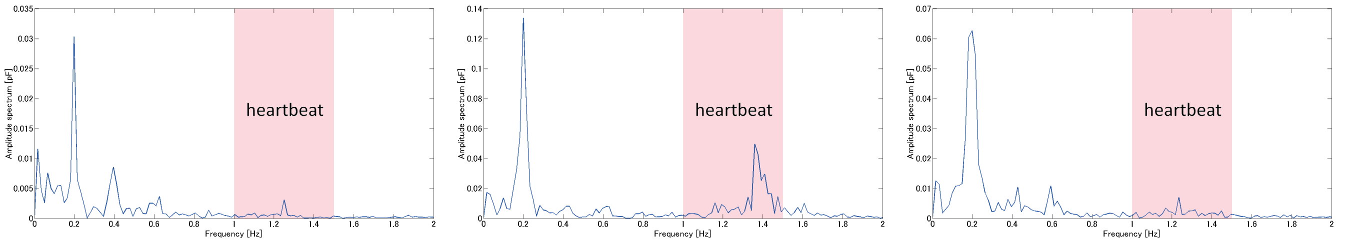
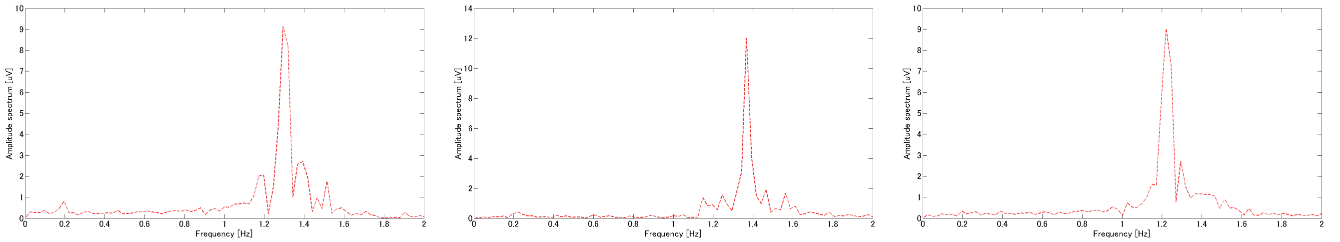


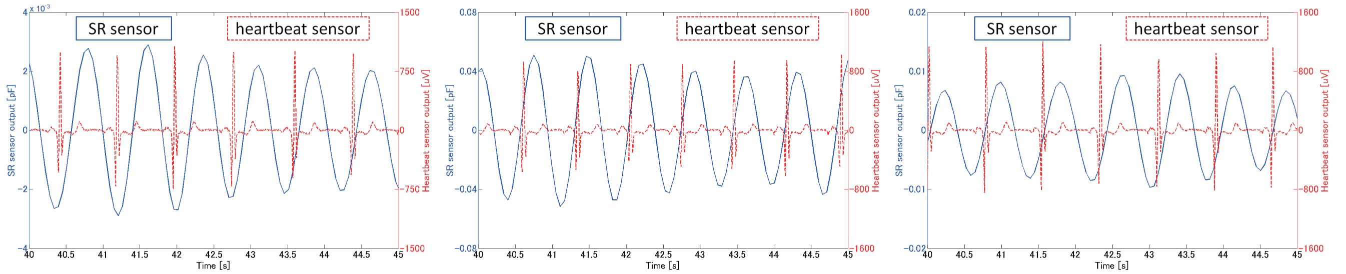
on his back on his stomach on his side

Figure 9. Frequency spectrums of the three postures by applying the FFT to the body pressure for measuring heartbeat.



on his back on his stomach on his side

Figure 10. Frequency spectrums of the three postures by applying the FFT to the output of the heartbeat sensor.



on his back on his stomach on his side

Figure 11. Measurement results of heartbeat of the three postures. The blue lines indicate the heartbeat waveform measured by our method. The red lines indicate the output value of the heartbeat sensor.