Effects of Sensor Type and Sensor Location on Signal Quality in Bed Mounted Ballistocardiographic Heart Rate and Respiration Monitoring

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Abstract— **Sleeping is a crucial part of our circadian rhythm and the quality of sleep has substantial impact on the quality of life in general and the overall well-being of a person. That is why sleep related physiological measurements have been in the focus of many scientific studies along the years, and why a large number of different measurement methods have been developed for this purpose. The ability to monitor heart rate respiration without any sensors or electrodes being directly attached to the body is extremely useful especially in long-term monitoring and it allows automated daily measurements without any medical staff present. This is the reason why ballistocardiographic force sensors and accelerometers have been introduced alongside electrocardiography (ECG) and thermistors or respiration belts as a means to monitor the heart rate and respiration during sleep. While ECG remains as the most reliable and accurate method for heart rate monitoring, the development of unobtrusive monitoring methods has improved to the point where the commercialization of such sleep monitoring systems has been possible. In this paper, the signals of five sensors and sensor placement combinations for measuring physiological parameters from a sleeping person are evaluated and compared in terms of their measurement sensitivities and waveform quality. The sensors are accelerometer and film type force sensors made of PVDF and EMFi material placed under the mattress topper and PVDF and EMFi sensors placed under the bed posts.**

I. INTRODUCTION

Humans are asleep approximately one third of their whole lifespan and the quality of one's sleep has a direct and significant effect on the time spent awake. Sleep deprivation has been shown, for example, to have negative effects on mental performance and health in general [1], [2], [3]. This is why the prevention and monitoring of the disturbances that happen during sleep have been studied extensively.

Sleep related issues and medical problems are common. In the United States alone, about 70 million people suffer from chronic sleep problems [4]. Diagnosis of these conditions has usually been done by using polysomnography (PSG), a method where multiple sensors are attached to the body of the patient. PSG is an accurate sensing technique, but it is expensive, since the recording is usually done in specialized facilities and trained professionals are needed to validate the results of automated interpretation of the signals. Furthermore, wearing a multitude of sensors may disturb the sleeping comfort of the patients [5]. Because of these reasons, PSG recording is usually done only in one night.

Ability to monitor sleep automatically at home using unobtrusive techniques would save resources and at the same time be substantially easier, cheaper, and more comfortable for an average person to get help and to follow his or her own condition. This would also enable long-term monitoring of sleeping patterns, which would in turn enable new possibilities for sleep research. However, the derived physiological parameters need to be accurate and the key point for this is a successful selection and placement of the sensing elements that are used to record the signals, from which the parameters are calculated.

II. RELATED WORK

Several different techniques for unconstrained monitoring have been attempted over the recent decades. In this study, we focus on methods that measure ballistocardiographic (BCG) and respiration movements with different kind of force or pressure sensors

The BCG sensors can be placed in several ways into the bed. In previous studies, the sensors have been installed under the bedposts [6], [7], under the pillow [8], to the bed frame [9] and on top of the mattress [10], [11], [12]. Special mattresses with integrated sensors have also been developed [13], [14], [15].

Different sensor structures and sensor materials have also been developed and used. There are multiple studies, where simple BCG sensors have been made from piezoelectric polyvinylidene fluoride (PVDF) film [11], [16], [17]. Permanently charged electret polymer material, EMFi (Electro Mechanical Film), is another example of a simple film type force sensor used in unobtrusive monitoring of sleep [18], [19]. PVDF and EMFi film sensors have also made their way to commercial markets with companies such as Beddit and EMFit using these sensor materials in their sleep monitoring systems.

Alternative more complex methods for BCG and respiration measurements include strain gauges attached to a slat under the mattress [9], and bedpost sensors based on the optical detection of beam deflection [6]. Also sensors comprising of a mat or tubes filled either with air or water to measure BCG signals have been proposed [14], [20], [21].

In this work, we focus on evaluating the properties of ballistocardiographic and respiration signals measured with piezo-electric PVDF and electret EMFi film sensors. Also the signals of a low-noise accelerometer are presented as a comparison.

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III. Measurement Setup and Tested Sensors

The measurement setup consisted of two smaller bed-post sensors made of PVDF and EMFi materials and two larger mattress sensors made of the same materials. In addition, a low-noise accelerometer was included in the measurement setup. ECG signal was recorded to obtain reference heartbeat locations.

A large PVDF sensor stripe (60 cm x 6 cm), similar to one used by Beddit Ltd in their bed monitoring solution, was used as one mattress sensor. When force is applied to the PVDF film the sensor produces a displacement charge due to the piezoelectricity of the material. This charge is converted to voltage by the capacitance formed by the sensor itself or, in case of a transimpedance amplifier, by the feedback capacitor of the amplifier. In addition to the mattress embedded PVDF sensor, a smaller PVDF sensor (40 mm x 20 mm) was located under the top-left bedpost.

The other tested mattress sensor, having dimensions of 40 cm x 40 cm, was manufactured from EMFi film. EMFi, as a material, is biaxially oriented thin polypropylene film that can be utilized as an electret. Due to its high resistivity and unique voided internal structure, the material can store large permanent charges that give it high sensitivity [22]. A smaller EMFi sensor (22 mm x 11 mm) was placed under the top-right bedpost. The main difference between PVDF and EMFi materials is that EMFi is mainly sensitive only to the force component perpendicular to its surface whereas the PVDF material has several piezoelectric coefficients in the same order of magnitude [23].

The low-noise accelerometer used in the experiment was SCA61T1H1G manufactured by Murata. It was placed along with the film-type mattress sensors under the mattress topper approximately to the location of the heart. The noise density of the sensor is, according to the datasheet, $0.0008 \, °/\sqrt{Hz}$ and the RMS-noise through the bandwidth of 10 Hz of the sensor becomes $0.0025°$. The component is normally used as an inclinometer and hence the noise is reported as degrees. In SI-units for acceleration, the corresponding RMS-noise is $4.34*10^{-4} \, ms^{-2}$.

The signal capturing was performed with a high-quality custom made 16-bit data acquisition (DAQ) device. The input range of the DAQ was ± 2.1 V resulting in 64 μV quantization step size. The RMS noise level of the DAQ was measured to be less than 1 LSB.

The measurements were conducted with five healthy adult test subjects. The subjects were lying on the foam mattress test bed for approximately ten minutes in each of the four main sleeping postures: supine, left side, right side, and prone. The results section shows example signals from one test subject in right side sleeping posture. Another test was performed to evaluate the effect of PVDF mattress sensor position on the recorded signals. The subject was lying in supine posture while the position of the sensor was changed in steps of 7 cm and signal was recorded for one minute in each sensor position.

The data collection and preservation have been done according to the principles of World Medical Association's Declaration of Helsinki.

IV. Results and Discussion

Even though the exact waveforms of the sensor signals vary between people and sleeping posture, there are generalizable differences in the signals acquired from different sensor locations.

The output amplitudes of the sensors vary depending on the sensor material and sensor placement. The RMS output charge of the film sensor elements is calculated according to Eq. (1)

$$Q = VC \; , \qquad (1)$$

where V is the RMS amplitude of the measured voltage and C is the combined capacitance of the sensor element and the cable. The measured capacitances of the sensors were 0.60 nF for the bedpost (BP) EMFi sensor, 1.6 nF for the BP PVDF sensor, and 45.5 nF for the mattress EMFi sensor. As said earlier, the PVDF mattress sensor was similar to what is used in a commercial sleep monitoring system. It included a built-in and sealed pre-amplifier, which prevented measuring the output of the piezo-electric sensing element solely.

The average RMS amplitudes of the output signals of the sensors are shown in Table I for the subject 1 when lying on the right side. The respiration and heartbeat components of the signals were separated for different pass bands by filtering the sensor signals with 10th order low-pass and high-pass filters both having 0.5 Hz cut-off frequency. As can be seen by comparing the RMS values of the heartbeat and respiration components of each force sensor, the sensors placed under the mattress topper, near the thorax have higher sensitivity to respiration movements than to heartbeats. The respiration component has been especially weak in the BP EMFi sensor. The same conclusion can be drawn by looking the signals in Fig. 1. The signals were normalized in order to enable observing and comparing their waveforms when drawn to the same figure.

The output amplitude or sensitivity of a sensor is not the most important parameter for evaluating sensor's capability of measuring the desired input signals. The most important aspects are the overall signal-to-noise ratio (SNR) of the quantized signal and consistency of the waveform of acquired physiological signal. Consistency is important for enabling accurate and reliable detection of the desired events e.g. heartbeats from the signals.

TABLE I.   RMS Amplitudes of the Sensor Signals for Subject 1 in Right Side Sleeping Posture.

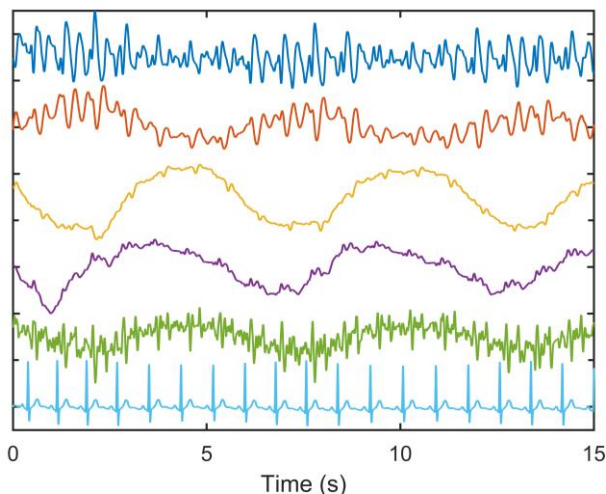| Sensor type	RMS amplitudes of sensor output signals	
	Respiration component	*Heartbeat component*
BP EMFi	1.57 pC	27.4 pC
BP PVDF	26.6 pC	26.3 pC
Mattress EMFi	414 pC	42.1 pC
Mattress PVDF	133 mV	26.3 mV
Accelerometer	0.80 mV / 0.0079 m/s^2	0.73 mV / 0.0072 m/s^2
ECG	0.028 mV	3.6 mV (peak-to-peak)

Figure 1. Signals measured using different ballistocardiographic sensors and sensor locations. The signals are normalized approximately to same amplitude scale in order to facilitate observing and comparing the waveforms. The signals from top to bottom are: bed post EMFi, bed post PVDF, mattress EMFi, mattress PVDF, accelerometer, and ECG.
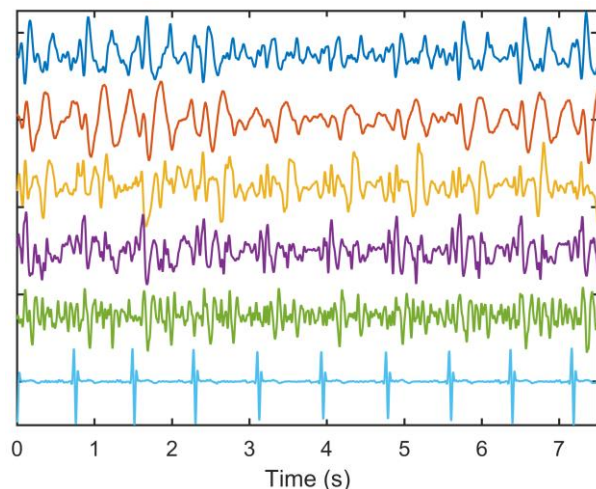

Figure 2. Ballistocardiographic heartbeat component is seen at the signals after high-pass filtering 10th order filter with 0.5 Hz cut-off frequency and then calculating discrete difference of the signal. The colors of the signals are the same as in Fig. 1.

Fig. 2 and Fig. 3 show separated heartbeat and respiration related signal components. The same color coding as in Fig. 1 is used in Fig. 2 and Fig. 3. Besides high-pass filtering, also a discrete difference has been taken from the signals in Fig. 2. The difference was taken to emphasize the high frequency components which are stronger at each heartbeat and thus to make the heartbeats more distinguishable. Discrete difference has been earlier used by several authors [11], [18], [19].

As seen from Fig. 2, there is more breathing related BCG amplitude variation in the signals measured with the bedpost sensors. Methods have been developed for compensating this variation because it decreases the reliability and accuracy of the heartbeat detection [24]. However, it may be argued that it would be better for the success of the heartbeat detection if such variation was minimal in the first place, i.e. another sensor location would be used. The BCG waveform of the accelerometer signal is the least consistent from the tested sensors. It is possible that also vibrations from the environment are coupled to the sensor signal decreasing the SNR. It must be mentioned that different signal pre-processing parameters are optimal for different sensors. For example the heartbeats can be made some more visible in different signals by varying the cut-off frequency of the high-pass filter. The parameters used for Fig. 2 are somewhat a compromise for all the signals.

Fig. 3 shows the respiration component of the example signals. The respiration components of the mattress sensors were clean, sinusoidal kind waveforms. Quite often BP EMFi and in some cases also BP PVDF showed strong distortions in the waveform as demonstrated in Fig. 3 for BP EMFi (blue signal). Methods for reliable monitoring of respiration rate from these kinds of signals have also been developed [25] but choosing a sensor that produces unambiguous signal waveform is still a preferable option. The quality of the bedpost EMFi signal is not this poor in all cases. It appears that sideways sleeping posture produces more distortion to the signals. Respiration is also seen in the baseline of the ECG but as seen from Table 1, this variation is small and it is therefore easily drown in movement artefacts.
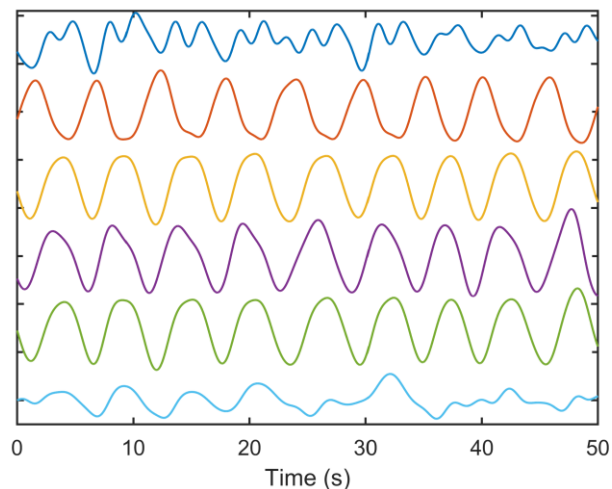

Figure 3. Respiration component seen after low-pass filtering the sensor signals at 0.5 Hz. The colors of the signals are the same as in Fig. 1.

Fig. 4 shows the locations of the mattress PVDF sensor relative to the subject when testing the effect of the sensor location. Fig. 5 shows the RMS amplitudes of the BCG and respiration components measured from these locations. Even though the signal amplitude is the largest when placing the sensor under the chest area, both BCG and respiration components are clear at almost all sensor locations. Fig. 6 shows the BCG and respiration waveforms measured from the locations 4, 11, 16, and 19 as an example.
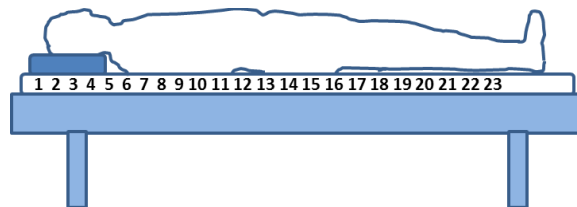

Figure 4. Sensor positions used in testing the effect of the position to the signal quality with mattress PVDF sensor.
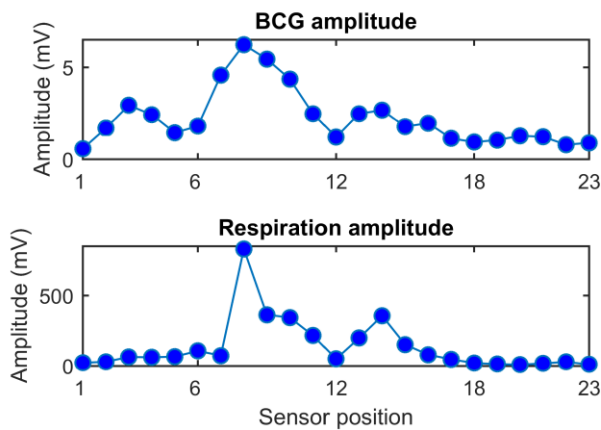
Figure 5. RMS amplitudes of the BCG and respiration signals recorded at different sensor locations.
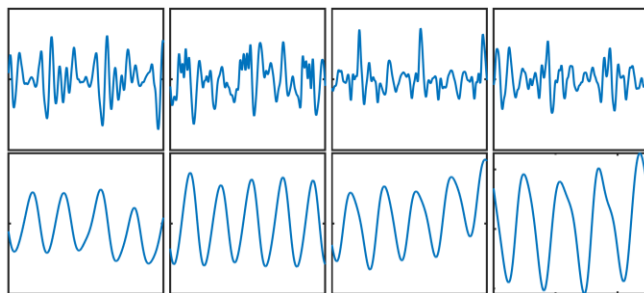

Figure 6. Example waveforms from sensor locations 4, 11, 16, and 19.

V. Conclusions and Future Work

The paper evaluated the differences in signals measured with film type force sensors made of PVDF and EMFi materials and located under the bed posts or under the mattress topper. Also an extremely low noise accelerometer was included in the measurement setup. The SNR of all force sensors was adequate and in the same order of magnitude by visual inspection. Overall, both heartbeat and respiration components are represented the best in the signals measured with the mattress force sensors. An interesting part of future work would include an evaluation of the situation of accompanied sleepers to see the differences in signal cross-talk between the sensor setups.

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