Feasibility Study of Developed Wearable Belt-type Capacitive Sensor for Apnea Monitoring

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Abstract. The purpose of this study was to design and develop low cost and easy-use wearable respiration monitoring system using capacitive sensor for individuals with respiratory disorders. The developed system monitors respiration patterns and gives alarms to notify any respiration abnormality in real-time breathing including apnea. The performance of our wearable belt-type capacitive sensor (WBCS) was compared with that of BIOPAC sensor for accuracy and clinical feasibility. Three male subjects in their 20s participated in this study to determine the feasibility of WBCS. Capacitive sensor was applied on the abdomen (T10) area by using an adjustable elastic waist belt. For the experiment, 4 breathing conditions were used for peak detection analysis: normal breathing (NB), fast breathing (FB), deep breathing (DB), and intentional apnea (IA). Each subject performed the 4 types of breathing for 1-minute each with 1-minute break in between. MATLAB was used for signal processing and moving average filter was used for noise filtering. Data was sampled at a sampling frequency of 100Hz and a cut off frequency of 10Hz. After signal processing, peak detection analysis was performed for both WBCS and BIOPAC. The results showed that the number of peaks detected by the two sensors was 100% consistent, and the peak deflection point detection was 95% consistent. WBCS can be used for the patients with respiratory diseases to prevent aggravation of conditions and sudden deaths. Future studies will include infants with respiratory disorders as subjects so our monitoring system could be a helpful healthcare system for developing countries to possibly prevent infant deaths caused by apnea.

Keywords: Wearable, Capacitive Sensor, Respiration, Apnea

1 Introduction

Respiration is one of the vital signs that need to be monitored and cared for healthy life. According to the WHO statistics and number of previous studies, breathing-related problem is the most dangerous cause of death both in industrialized and developing world [1]. The most common respiratory diseases include chronic obstructive pulmonary disease, asthma, acute respiratory infections, tuberculosis, and lung cancer [2]. All of the aforementioned respiratory diseases and abnormal breathing patterns including sleep apnea need to be well monitored and treated early because they can lead to death. For both daily and clinical healthcare, respiratory rate (RR) is often monitored and studied by many researchers. However, the measurement method is usually limited to laboratories and sensor attachments are uncomfortable for the participants. Currently, many researchers are developing various forms of wearable sensors and smart clothing system aiming to investigate effective and accessible products for health care and biomedical application [3,4]. Wearable sensors in the form of flexible electronics textile (e-textile) are advantageous due to their physical flexibility, accessibility, and integration of interconnections to various electronic interfaces. Smart clothing and wearable sensors showed promising results in the field of health care, especially in the development of noninvasive, efficient, and comfortable system for diagnosis and therapeutic approach [5-7]. When monitoring is the key function of a wearable device, user's comfort is the most significant factor to be considered. Accuracy, power efficiency, and cost are also important. Therefore, this study aimed to develop a low-cost, easy-use wearable respiratory monitoring device for potential respiratory patients in all ages.

2 Methods and Materials

2.1 Capacitive Respiration Sensor

A capacitive sensor can be formed with two reference capacitors and use the electrical property of capacitance to make measurements. The voltage output V is proportional to the deflection of the membrane Δx. Changes in the distance between the surfaces alter the capacitance. This change is detected and used by the capacitive to indicate positional changes of a target Capacitive pressure sensors use thin diaphragms, usually metal or metal-coated quartz, as the capacitor plate. The diaphragm is exposed on one side of the sensor where pressure is to be applied. The other side is a reference sensor. Any change to the applied pressure on the sensor causes deflection and alters the capacitance of the capacitor [8].

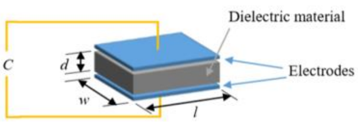

Figure 1. Capacitor Configuration

Changes in capacitance are calculated by the following equation

$$C = \varepsilon_0 \varepsilon_r \frac{A}{D} \quad (1)$$

Where, C is capacitance of the capacitor, A is cross-sectional area, D is estimated distance between the plates, ε_0 is dielectric constant (specific to different dielectric material) and ε_r is relative permittivity of free space.

2.2 Capacitive Respiratory Textile Sensor Design

The developed wearable belt-type capacitive sensor (WBCS) is designed to have 5 layers containing two conductive plates, one dielectric plate interlining between the conductive plates, and two outermost cover plate for protection. The dimension of the sensor was 30*30*2mm (Length*Width*Distance; D is the thickness of dielectric material), and was designed to detect respiration pattern from abdominal expansion. The size of a sensor affects accuracy, sensitivity, and frequency response [9]. Capacitive sensor was selected over piezo-resistive sensor because of its compatibility for the intended use in this study; it has higher temperature resistance, sensitivity, frequency response, and linearity [10].

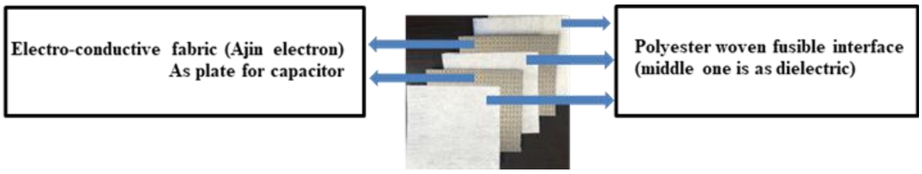

Figure 2. Textile Capacitive Sensor

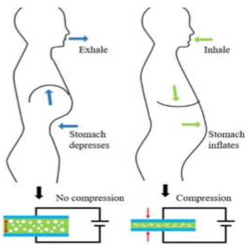

Figure 3. Data Acquisition and System Configuration

2.3 Experimental Procedure and Laboratory Setting

Three healthy males in their 20s participated in the study. The subjects were instructed to perform 4 conditions of breathing in a random order by sitting in a given chair with 90˚ hip flexion, 90˚ knee flexion, 90˚ ankle flexion, and straight-back supported against the back of the chair as shown in Figure 4. For respiration baseline (normal breathing; NB), each subject was asked to breath naturally and comfortably in a resting state. For fast breathing (FB), the respiration rate of NB was doubled. For deep breathing (DB), the rate of NB was reduced in half. For intentional apnea (IA), subjects were to hold their breaths for 10 seconds. Each of the 4 breathing conditions was performed continuously for 1 minute with 1-minute break in between.

Biomedical signal acquisition device MP150 (BIOPAC, USA) was used for data comparison analysis.

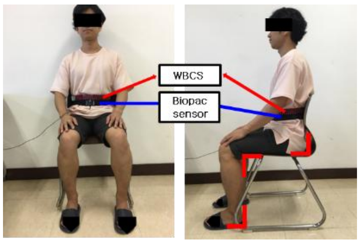

Figure 4. Laboratory Set-up

2.4 Sensor Output and Analysis

C#application system for bluetooth-based signal acquisition was developed for this study. MATLAB was used for signal processing and moving average filter was used for high frequency noise filtering. Data was sampled at a sampling frequency of 100Hz and a cut off frequency of 10Hz. After signal processing, peak detection analysis was performed for both WBCS and BIOPAC. Peak deflection point was detected by using findpeaks function provided by MATLAB library. Data filtering sample of WBCS is shown below in Figure 5 and comparison sample of the two sensors is shown in Figure 6.

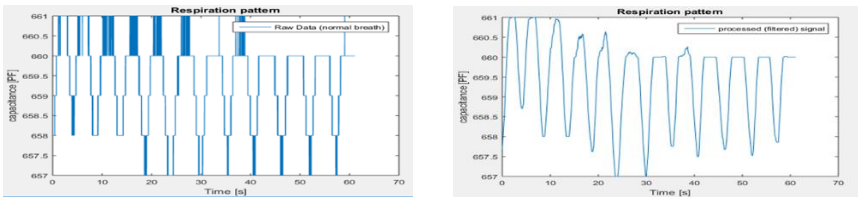

Figure 5. Respiration Data from WBCS [Left: raw data, Right: filtered data]

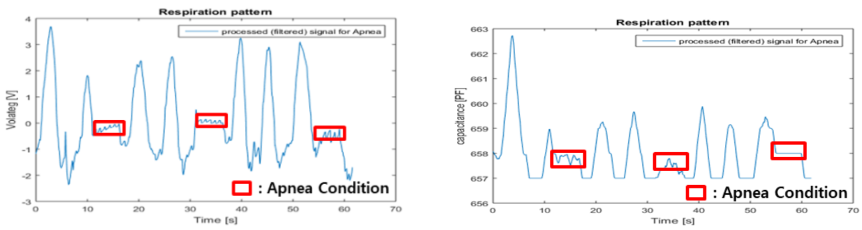

Figure 6. Comparison of Apnea Detection [Left: WBCS, Right: BIOPAC MP150]

2.5 Experimental Results

The accuracy of WBCS and Biopac was compared by peak detection analysis. The number of peaks detected by the two sensors during 1-minute respiration (RR) was 100% consistent in all subjects (NB: 11, 13, 15, FB: 35, 20, 42, DB: 7, 13, 8, IA: 2&5,

4&7, 3&8th peaks, respectively in subject 1, 2, 3). Peak deflection point detection was 94.4% consistent in average (95.0, 95.5, 92.7%, respectively in subject 1, 2, 3). For analysis, the first and the last data of each subject's RR were deleted. The peak deflection point comparison result of Subject 1 is shown below in Table 1 as a sample. The sampling frequency range was between 2500 and 3500.

Table 1. Peak deflection point detection result of Subject 1

Sensors	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Average
Biopac	2663	2675	2686	2698	2824	2841	3302	3311	
WBCS	2601	2615	2638	2644	2646	2666	2962	3030	
Consistency %	97.6	97.8	98.2	97.9	93.6	93.8	89.7	91.5	95.0

3 Discussion

This study aimed to develop cost-effective, easy-use wearable respiration monitoring device. Respiration monitoring is based on RR, which is the number of breaths per minute. RR is one of the key parameters used in the clinical setting as it is one of the vital signs that must be cared for survival or maintenance of life. Therefore, monitoring of RR and the related abnormalities is an important diagnostic method in planning efficient medical care. The patients with respiratory disorder suffer from shortage of oxygen in their blood and brain which leads to physiological malfunction, even sudden death.

WBCS was designed to monitor real-time respiration pattern of the wearer and give alarm every time any abnormality in breathing is detected. The performance and accuracy of the developed sensor WBCS was compared with the commercially available BIOPAC system for feasibility testing. The results showed that the number of peaks detected by the two sensors was 100% consistent, and the peak deflection point detection was 94.4% consistent in average.

Limitations of this study were small number of subjects, recruitment of only healthy males in their 20s, and analysis of breathing only in sitting posture. Future studies will recruit more number of subjects with broader age range including infants with respiratory disorders, and analyze breathing patterns in various postures for longer periods of time so that WBCS could be a helpful healthcare system for all ages as well as for developing countries to possibly prevent infant deaths caused by apnea.

4 Conclusion

Cost effective, easy-use, comfortable respiratory monitoring sensor WBCS was developed in this study and showed promising results in detecting 4 different breathing patterns. WBCS can be used for patients with respiratory diseases to prevent aggravation of conditions and sudden deaths.

Acknowledgement

This research was supported by the Bio & Medical Technology Development Program of the National Research Foundation (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2015M3A9D7067388).

This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2018-2014-1-00720) supervised by the IITP (Institute for Information & communications Technology Promotion).

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