

A Wearable Device for Continuous Cardiorespiratory System Monitoring

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Abstract—This paper describes the design and implementation of a wearable monitoring device for performing a continuous inspection on the cardiorespiratory system based on the Heart Rates (HR) and Respiration Rates (RR). The HR and RR are the two vital signs as relevant indicators to show the functionality and wellness of the cardiorespiratory system. The device consists of a bell-shaped stethoscope, which is attached to a capacitive microphone, and a FM radio transceiver to establish a wireless connection between the measuring sensor and collecting device which is held off body. In order to obtain the HR values a simple peak detection scheme is applied to the measured sound signals to count the number of Beats Per Minute (BPM). In contrary to the direct measurement used for obtaining the HR values, the interaction between the heart and lungs (i.e., Mechanical modulation of the heart by the lungs) was considered. Such modulation leads to eliminating the need for of a respiration sensor. Also, the HRR value, which is introduced as the ratio of the HR and RR value, is used to assess the health condition of the cardiorespiratory system.

Index Terms—Wearable device, health monitoring, heart and respiration rate inspection.

I. INTRODUCTION

Over the past decade, a large number of health monitoring wearable devices have been presented to continuously obtain the human body's vital signs such as SpO_2 , Electrocardiography (ECG), body temperature [1], Electroencephalography (EEG) and respiration [2] benefiting the advances in developing low-power electronics in conjunction with the emerging Information Technology (IT) and its applications in remote health monitoring, sports and long-term patient inspection [3][4]. Developments in wearable health monitoring devices particularly for cardiorespiratory system enables early stage detection of diseases such as abnormal breathing, heart unresponsiveness as well as apnea [5] at rest and daily living activities. The premier approach in performing an inspection on the cardiorespiratory system is to monitor the Heart Rate (HR) and Respiration Rate (RR), which are usually measured as the two significantly important indicators, besides their ratio (i.e., $\text{HRR} = \text{HR}/\text{RR}$) [6]. To detect cardiorespiratory system diseases at their early stage, it is essential to monitor the HR, RR as well as HRR not only in stationary situations but also during the daily activities without constraining the daily activities of the bearer (e.g., The patient wearing the device). To date, examples of such monitoring devices which incorporate the

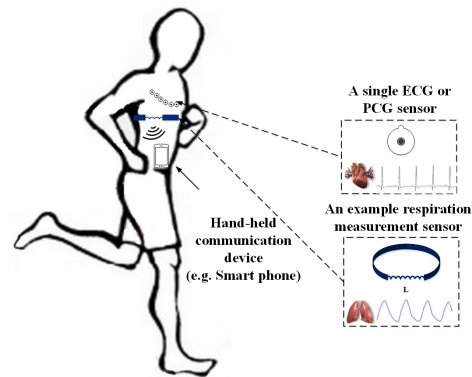


Fig. 1. A typical wearable device for cardiorespiratory health monitoring.

ECG electrodes and accelerometer sensors [7][8] in addition to respiration sensors (e.g., Chest cuff) were extensively reported in literature. They usually consist of at least two sensors one for detecting HR and a separate sensor for RR measurement as reported in literature [9][10]. Fig. 1 schematically shows a typical wearable device incorporating two separate sensors which are used to obtain the HR and RR values. As it can be seen, the example system comprises a set of ECG electrodes for obtaining the HR and a respiration sensor, for instance a stretchable chest cuff whose length changes (ΔL) during the course of an inhale and exhale [7], used for estimating the RR values. An investigation showed that the wearable devices for monitoring the cardiorespiratory are usually bulky, heavy and non-portable in addition to being not comfortably wearable. Such devices are also sensitive to ambient and surrounding environment noise [11]. A number of low-profile monitoring devices such as the differential ECG pair which consists of a pair of two ECG electrodes was previously proposed [12], however, such devices are also prone to artifacts and electrical interference [13]. An alternative approach to measure HR is monitoring of the acoustic sound signals generated due to the various activities of the heart including movement of valves and blood flow in the heart vessels besides contraction and relaxation of the myocardium [14]. These sounds can be detected via a stethoscope [15] which is called phonocardiography (PCG). Typically, the corresponding sound

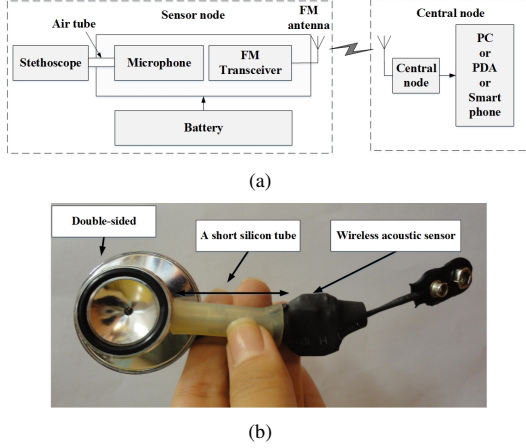


Fig. 2. The developed wearable device for cardiorespiratory health monitoring (the wireless stethoscope), a) Schematic of the constructing blocks, b) a photograph of the developed wireless stethoscope.

for a heartbeat includes two signals denoted by the S_1 and S_2 which are separated by a specific duration (i.e., t_{s-s}) [16]. Therefore, the HR value corresponds to occurring the number of the S_1 or S_2 signal's peaks over a minute. This leads to a reduced errors in obtaining the actual HR values in addition to being less sensitive to ambient noise and artifacts [17] as opposed to the system utilizing ECG electrodes. Also, it should be noted that similar to the approach reported in [10], another sensor is needed to detect RR.

In this paper, the design and realization of a wearable device, which seemingly looks like a wireless stethoscope, is presented to measure both the HR and RR values simultaneously by using only an individual sensor. Additionally, the device can estimate the ratio of the HR and RR, denoted by HRR, in order to monitor instant health condition of the patient who already diagnosed for a complication with the cardiorespiratory system regardless of the intensity of the daily activities (i.e., context-aware health monitoring) [18].

II. THE PROPOSED WEARABLE DEVICE

The wearable device which is presented here enables HR and RR measurements in a continuous manner as shown in Fig. 2. As it schematically shown in Fig. 2a, the developed wearable device consists of three essential elements namely, sensing and communication units in addition to a power supply. Amongst, the sensing unit is the most essential part of the device which detects the acoustic signals generated due to heart activity by using a capacitive microphone is attached to a bell-shaped stethoscope via a silicon tube with a length of 3 cm (Fig. 3a). Longer and shorter tubes were also tested, however, the obtained results were not promising as represented in Fig. 3b and 3c. The bell-shaped stethoscope is used to increase the Signal to Noise Ratio (SNR) besides reducing the surrounding noise as shown in Fig. 2b. The communication part consists in using a radio frequency FM transceiver, operating over a frequency band ranging from 88-108 MHz, whose main functionality is to transmit the

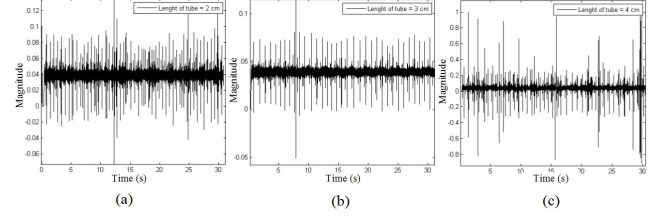


Fig. 3. The effect of tube length (L_T) connecting the stethoscope for the wireless microphone. (a) $L_T = 2$ cm, (b) $L_T = 3$ and (c) $L_T = 4$ cm.

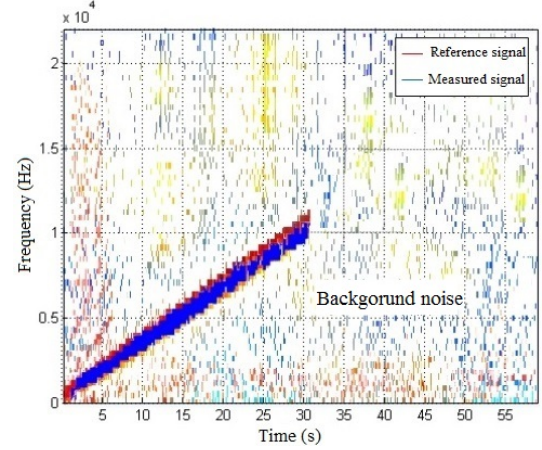


Fig. 4. The Short-Time Fourier Transform (STFT) of the captured signal by developed device.

obtained signal to a collecting device (i.e., The receiving unit) which is held away. The receiving unit enables the measuring device to select different frequencies to prevent interference with the nearby devices may possibly operate at a designated frequency, to establish a collision-free transmission of the obtained signals.

A. Frequency Characteristic of the Developed Wearable Device

To ensure that the developed device is able to captured the sound signals generated by the heart over the specific frequency band ranging from 48 to 1024 Hz, the frequency response of the device was obtained. To this end, a sound signal whose frequency was gradually increased from 0 to 11 KHz over a duration of 30 seconds was generated by a calibrated speaker as the reference signal while the developed device simultaneously measuring the sound signals. Fig. 4 shows the reference line and the results obtained from the measurement. As it can be seen, both curves follow each other and are convincingly matched, confirming the desired frequency characteristic of the developed device.

B. Sensing Unit– A Dual Functionality Sensor

Since the designed wearable device is supposed to measure both the HR and RR values, therefore, it is intuitive to incorporate two separate sensors in construction of the device

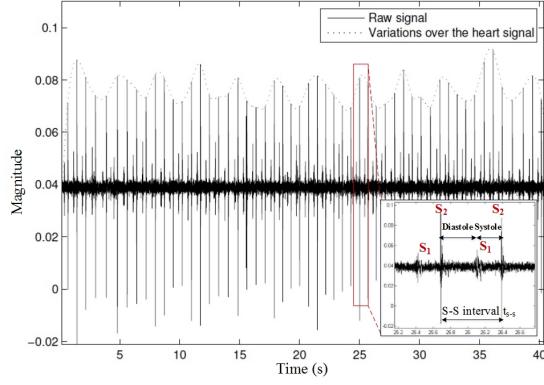


Fig. 5. An example of the heart sound signal measured by the developed device.

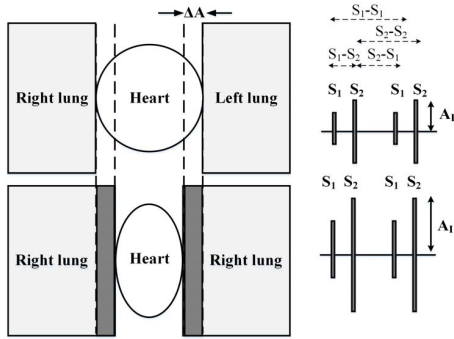


Fig. 6. The schematic showing the heart and lungs interaction.

that causes the sensor's structure becomes more complex and bulky. To this end, the interaction between the heart and lungs, which is basically the effect of lungs activity on the heart's sounds, was taken into account so as to eliminate the need to incorporating additional sensor for RR estimation. The simplified mechanism of the interaction is schematically represented in Fig. 6. The raw measurement data obtained by using the device includes a number of peaks that each corresponds to a heartbeat as can be observed in Fig. 5. As a consequence, heartbeats can be obtained by executing a peak detection algorithm. The fluctuations observed on the amplitude of the measured data looks like a low frequency envelop signal to the measured raw signal. An investigation revealed that the cause of fluctuations, is the interaction between the heart and lungs as it is schematically demonstrated in Fig. 6. The interaction results in a continuous changes of the amplitude of the measured signals during the inhalation and exhalation process. In Fig. 6, the amplitude of the sound signal generated by heart is weaker during the exhale (i.e., A_E) compared to an inhale (i.e., A_I). Such variation in the amplitude of the sound signals can be interpreted as the modulation of heart's activity by the lungs while inhale and exhale occur in series. Therefore, the envelop of the modulated signal and its frequency, respectively, are referred to as lung activity and the respiration rate (i.e., RR).

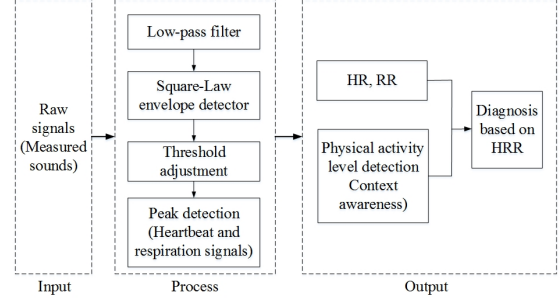


Fig. 7. Block diagram showing the data processing procedure utilized to obtain the HR and RR values.

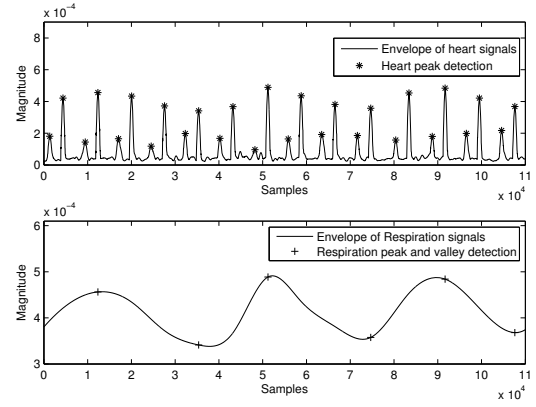


Fig. 8. An example of the heartbeat and respiration signals at the output of the envelope detector.

III. EXPERIMENTAL EVALUATION OF THE DEVELOPED WEARABLE DEVICE

Fig. 7 shows the block diagram of the data processing unit in which the raw data is processed to obtain the HR and RR values, and consequently HRR. In the data processing unit the signal obtained from measurement was first filtered by using a 4th order low-pass Butterworth filter with a cut-off frequency of 200 Hz to suppress spurious signals and also the ambient noise. An envelope detection scheme, which mainly consists in squaring and down-sampling operations, was applied to the filtered out signal [19]. Fig. 8 represents the obtained signals corresponding to the heartbeat and respiration rate.

In order to evaluate the performance of the developed device, it was set to measure the HR and RR of a 25 years old healthy volunteer, with no history of cardiorespiratory disease [20], which are calculated by (1) and (2)

$$HR = \frac{60}{t_{S-S}} \quad (1)$$

$$RR = \frac{60}{t_{R-R}} \quad (2)$$

where the t_{S-S} and t_{R-R} are defined, respectively, as the interval between two successive S_2 signals' peak and two peaks' interval of the respiration signal (Fig. 8).

TABLE I
THE HR, RR AND HRR VALUES AT DIFFERENT PHYSICAL ACTIVITY LEVELS

Type of Activity	Time (s)	Speed ($\frac{Km}{h}$)	Avg. HR (min.)	Avg. RR (min.)	HRR
Rest (mostly sitting)	900	—	68	13	5.23
Lying	900	—	65	12	5.41
Slow walking	120	2.5	84	16	5.25
Normal walking	120	4.6	92	20	4.6
Jogging	120	7.1	101	16	6.31
Running	120	8.3	136	19	7.15
Fast running	120	8.9	168	20	8.4
Stair climbing	120	—	169	25	6.76
Down 50 steps, up 50 steps	—	—	—	—	—
No respiration in rest	60	—	74	—	—
Recovery period	360	—	69	13	5.3

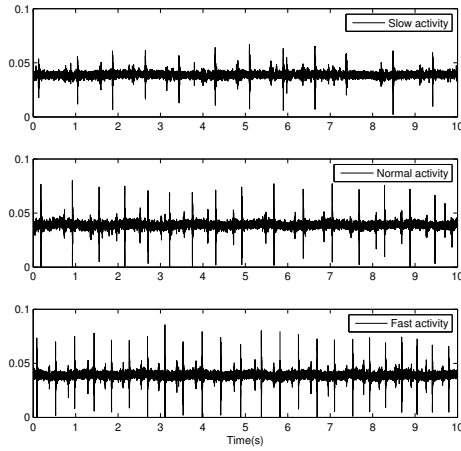


Fig. 9. The obtained results by using the developed device; (a) walking, (b) jogging, (c) running.

IV. MEASUREMENT RESULTS AND DISCUSSION

As it was noted earlier, the HR and RR in addition to their ratio (i.e., HRR) are the measures reflecting the wellness and health condition of the cardiorespiratory system of the human body [21]. Normally, the HR and RR can vary over a range of 60-100 and 12-20, respectively. The HRR values independent of the intensity of activity levels usually are located between the range of 3 to 8 for healthy individuals that these thresholds were obtained from different combination ratios of the HR and RR values. Fig. 9 shows the measured HR and RR values of the healthy volunteer obtained at rest, while jogging and also running. The HRR values related to the measurements in Fig. 9, are shown in Fig. 10. The results reveal that the HRR deviates from the desired upper threshold that this situation may endanger the health of volunteer if the activity proceeds without lowering the endeavoring activity. A sets of HR, RR and HRR values obtained from measurement are also presented in the Table I. The HR value of the volunteer while running are shown in Fig. 11. As it can be observed, the HR values increases suddenly when the runner's speed exceeds ~ 9.5 Km/h.

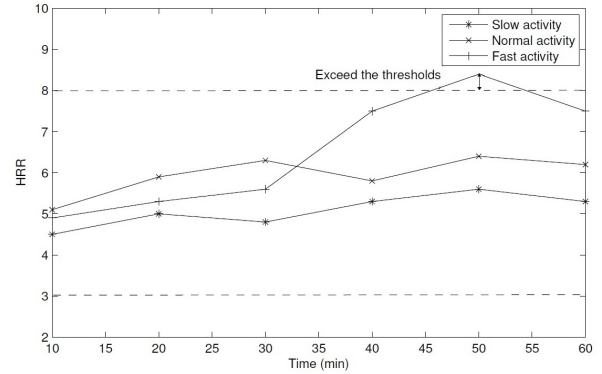


Fig. 10. The HRR values versus activity duration.

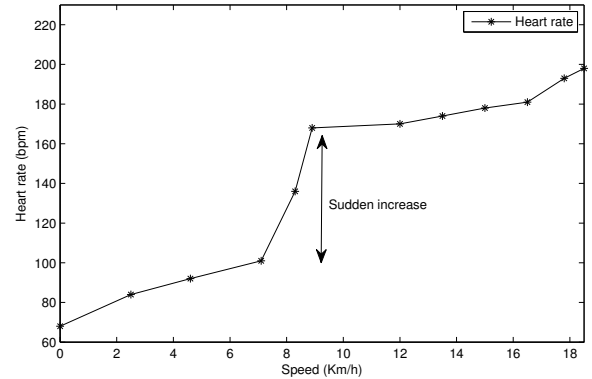


Fig. 11. The measured HR values against different running speed of the volunteer.

A. Arrhythmia diagnosis

One of the perceivable applications for the developed device is to use for diagnosing the diseases and complications associated with the cardiorespiratory system, generally referred to as Arrhythmias, such as bradycardia, tachycardia and also uneven heartbeat which is an indication for disorders in ventricular or arterial fibrillation. For instance, bradycardia stands for HR lower than the normal value (i.e., 60 BPM in healthy adults) [22] can be detected by the developed device. As an

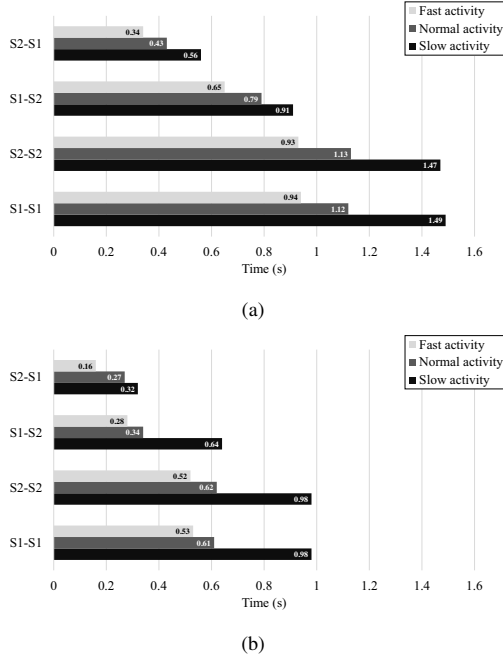


Fig. 12. Averaged intervals between heart sound signals in normal state at slow, normal and fast activity over a period of 30 minutes in a) unhealthy person and b) healthy person.

complementary test, a 25 years old volunteer diagnosed with bradycardia arrhythmia participated the test for 30 minutes by performing slow, normal and fast activities. According to the measured data, it was found that beside HR and RR monitoring, it is possible to diagnose arrhythmia of the patient by measuring the variation of the time interval between the sets of $S_1 - S_2$, $S_2 - S_1$, $S_1 - S_1$ and $S_2 - S_2$ as it can be seen in Fig. 6. A healthy and unhealthy (e.g., diagnosed with bradycardia) volunteers performed the same activity that the obtained results are shown in Fig. 12. A comparison of the results for both volunteers revealed that the variations of the interval between the sets of S_i and S_j where $i, j=1$ or 2 , are significantly higher for the case the volunteer is diagnosed with an arrhythmia.

V. CONCLUSIONS

In this paper, the design and implementation of a wearable device for performing continuous cardiorespiratory monitoring were comprehensively described. It was shown that the developed device can measure both the heart and respiration rate by only using a sensor. This wearable device, which seemingly looks like a wireless stethoscope, can also be used for a variety of applications such as remote patient and athletes' health monitoring as well as inspecting the well-being of elderly people at home who are required to be continuously monitored. The obtained results over the monitoring period can lead clinical staff to more effective prescription and more accurate diagnosis of the different types of arrhythmia, such as bradycardia.

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