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Design of wearable and wireless multi-parameter monitoring system for evaluating cardiopulmonary function

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A B S T R A C T

The 6-minute walking test (6MWT) is the test most commonly used to evaluate cardiopulmonary function in patients with respiratory or heart disease. However, there was previously no integrated monitoring system available to simultaneously record both the real-time cardiopulmonary physiological parameters and the walking information (i.e., walking distance, speed, and acceleration) during the 6MWT. In this study, then, a wearable and wireless multi-parameter monitoring system was proposed to simultaneously monitor oxygen saturation (SpO_2), heart rhythm, and the walking information during the 6MWT. A multi-parameter detection algorithm was also designed to estimate the heart rate effectively. The results of the study indicate that this system was able to reveal the dynamic changes and differences in walking speed and acceleration during the 6MWT. As such, the system has the potential to provide a more integrated approach to monitoring cardiopulmonary parameters and walking information simultaneously during the 6MWT. The proposed system warrants further investigation as an assistive assessment tool in evaluating cardiopulmonary function and may be widely applied in cardiopulmonary-related and sports medicine applications in the future.

1. Introduction

The 6-minute walking test (6MWT) is the test most commonly used to evaluate exercise capacity and predict functional outcomes in patients with respiratory or heart disease. In 1985, Guyatt et al. [1] and Lipkin et al. [2] first used the 6MWT to measure the exercise capacity of patients with heart disease. The test is also used to assess prognosis and functional impairment in various respiratory diseases [3–5]. Recently, the 6MWT has also been applied in sports medicine and fitness activities [6].

The 6MWT, which follows the American Thoracic Society (ATS) guideline, is performed indoors along a long, flat, straight, and enclosed corridor with a hard surface. The evaluated parameters include the walking distance in meters and the change in oxygen saturation (SpO_2) as measured by a portable pulse oximeter [7]. The participant is instructed to walk as far as possible in six minutes [8]. Patients with lung disease and dyspnea can present an exercise limitation when performing the 6MWT due to insufficient ventilation in relation to metabolic demand, low breathing reserve, expiratory flow limitation, dynamic hyperinflation, and the retention of arterial CO_2 [9–11]. The 6MWT is a critical and useful test for clinical physicians seeking to determine the etiology of dyspnea, exercise intolerance, and therapeutic response and clinical improvement [3,4,10,12]. However, some patients with cardiopulmonary disease can develop arrhythmia or unstable ischemic changes during the 6MWT without real-time heart rhythm monitoring. Thus, it is necessary to develop a system that can provide real-time heart rhythm monitoring.

Recently, several systems have been developed to integrate the parameters of the 6MWT. In 1996, Nixon et al. [12] used a pulse oximeter to monitor heart rate and SpO_2 and to compare the exercise tolerance of the traditional exercise test with that of the 6MWT. In 2001, Chetta et al. [13] assessed walking distance, SpO_2, and breathlessness perception during the 6MWT. They marked the return point to record the number of turns and used a pulse oximeter to calculate SpO_2 at the end of the test. The test of 6MWT followed a standard protocol and breathlessness perception during the walk was assessed using the visual analogue scale (VAS, in mm) [14]. In 2008, Pandian et al. [15] proposed a vest integrated with several physiological sensors to monitor electrocardiography

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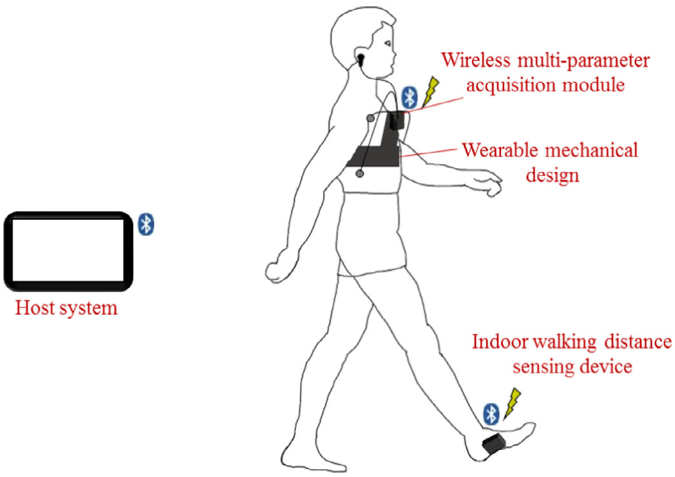

Fig. 1. Basic scheme of proposed wearable and wireless multi-parameter monitoring system.

(ECG), heart rate, blood pressure, body temperature, galvanic skin response (GSR), SpO_2 in the blood, respiratory rate, electromyogram (EMG), electroencephalogram (EEG), and three axis movements. In 2010, Tueller et al. [16] used an oxygen sensor, an ECG-triggered belt, and a facemask to detect SpO_2, heart rate, respiratory rate, and tidal volumes. In 2013, Heijden et al. [17] used a pulse oximeter and a spirometer to measure SpO_2 and lung function, respectively, and developed a disease management system for patients with chronic obstructive pulmonary disease (COPD) to help such patients self-manage their disease and prevent hospitalization. In 2014, Karpman et al. [18] reported that walking speed is an excellent screening tool to detect 6MWT performance in COPD patients. However, there was still a lack of a suitable integrated system for the simultaneous monitoring of both the real-time cardiopulmonary parameters [19] and the walking information (i.e., walking distance, speed, and acceleration) [20] during the 6MWT.

In this study, therefore, we propose a wireless multi-parameter acquisition module embedded in a wearable mechanical design to simultaneously monitor ECG, SpO_2, walking distance, walking speed, and walking acceleration during the 6MWT. To validate the accuracy of the proposed system, we invited normal healthy participants to test the system. Because the athletes have frequent exercise training, their cardiopulmonary function and exercise capacity would be better than those for the non-athletic group. In order to distinguish the characteristics of walking information, we divided subjects into the athletes and non-athletes group.

2. System hardware design and implementation

Fig. 1 shows the basic scheme of the proposed wearable and wireless multi-parameter monitoring system for evaluating cardiopulmonary function. The system consists primarily of a wireless multi-parameter acquisition module, a wearable mechanical design, an indoor walking distance sensing device, and a host system. The wireless multi-parameter acquisition module, which is embedded in the wearable mechanical design, is designed to monitor multiple signals simultaneously during the 6MWT. The wearable mechanical design was developed in order to provide a convenient and reliable measuring procedure. It allows the system to be easily worn by the user, and can also allow the sensors of the wireless multi-parameter acquisition module to maintain good contact with the body in order to effectively reduce the influence of walking on the SpO_2 and ECG measurements. The indoor walking distance sensing device was designed to monitor and record the user's indoor walking distance, walking speed, and walking acceleration.

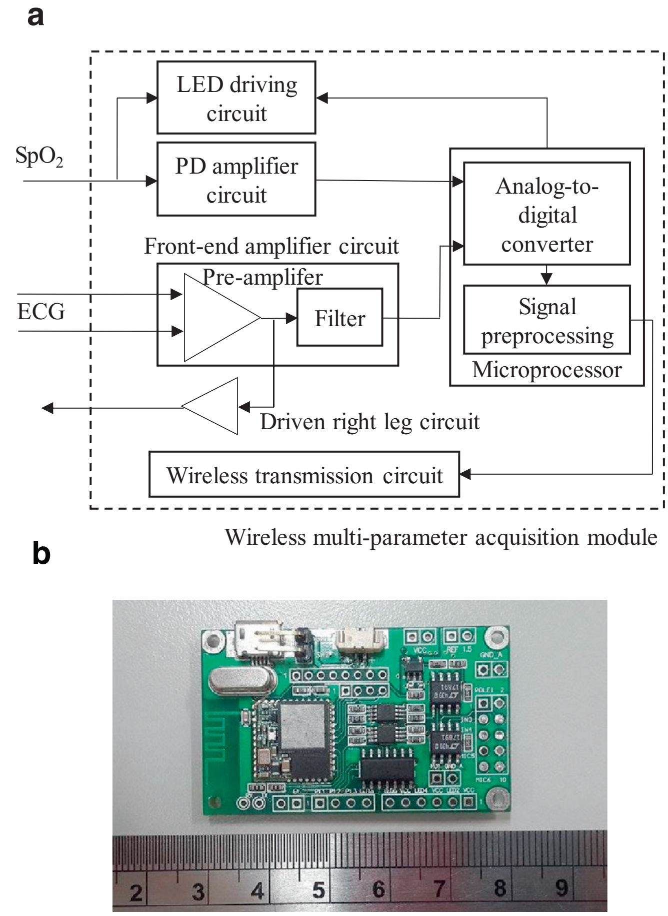

Fig. 2. (a) Block diagram and (b) photograph of proposed wireless multi-parameter bio-signal acquisition module.

According to the location of the ECG Lead II, a pair of primary input electrodes were placed, for each user, on the right chest between the fourth intercostal region and fifth intercostal region and on the left waist about fifteen centimeters left of the navel, respectively, and the reference electrode was placed on the right waist about fifteen cm right of the navel in order to acquire ECG signals [21]. The optical probe used to monitor SpO_2 was attached to the ear of the user to acquire SpO_2 signals. Next, these bio-signals were amplified and filtered by the wireless multi-parameter acquisition module, and were transmitted to the host system wirelessly via Bluetooth. Moreover, the walking distance sensing device was tied on the shoe side to monitor the walking distance. Finally, the multi-parameter monitoring program built into the host system continuously monitored these bio-signals to assist the physician in evaluating the cardiopulmonary function.

2.1. Wireless multi-parameter acquisition module and wearable mechanical design

Fig. 2(a) and (b) show the basic block diagram and a photograph of the proposed wireless multi-parameter bio-signal acquisition module. The wireless multi-parameter acquisition module operates at 31 mA with a 3.7 V DC power supply, and can continuously operate for at least 6 h with a commercial 250 mAh Li-ion battery. The size of the module is about $30 \times 50 \times 10\ mm^3$. It primarily consists of the following parts: a light-emitting diode (LED) driving circuit, a photodiode (PD) amplifier circuit, front-end amplifier circuits, a microprocessor, and a wireless transmission circuit.