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System design for wearable blood oxygen saturation and pulse measurement device

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Abstract

With the rapid development of information technology, the demands of sport monitoring research are rapidly increasing. Sport Internet of Things (IoTs) based on the sensor technique and modern communication technology are becoming more and more important to current sport training and daily activities. Sensor-based sport monitoring approaches lead people to take advantage of the wearable sport devices to monitor their own physiological parameters, in which we will focus on the blood oxygen saturation and the pulse measurement. In order to measure these two parameters, we will adopt near-infrared portable tissue oximeter with detection module using STM32 microprocessor. Near infrared spectroscopy (NIRS) is becoming a widely used research instrument to measure tissue oxygen (O_2) status non-invasively. Continuous-wave spectrometers are the most commonly used devices, which provide semi-quantitative changes in oxygenated and deoxygenated hemoglobin in small blood vessels (arterioles, capillaries and venules). Through the measurement using the near-infrared technology, we could obtain the blood oxygen saturation and the pulse parameters. After obtaining the above two parameters, the portable device will send the data to the remote coaches or doctors via GPRS/WiFi/Zigbee networks. The data of the blood oxygen saturation and the pulse that is detected by the detection module are processed by the expert decision-making system in order to provide the coaches and doctors with the athlete condition. In addition, the data can be sent to the smart phones of the players, coaches or doctors through GPRS/WiFi networks, in which the blood oxygen saturation and the pulse data of the athletes can be displayed according to the requirement of the remote users. The test results show that the accuracy of measurement is high and the system is stable.

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Keywords: Sport monitoring; Blood oxygen saturation; Pulse; GPRS/WiFi/Zigbee Networks

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1. Introduction

Wearable blood oxygen saturation and pulse measurement systems have been introduced by using mobile devices and wireless network to collaborate scattered sport Internet of Things (IoTs) resources. To enhance the mobility of blood oxygen saturation and pulse measurement systems, the efficiency of testing data and the reliability of fusion information, wearable system is deployed to surpass current applications. Wearable blood oxygen saturation and pulse measurement systems use medical sensors to monitor the required physiological parameters and process the obtained the data. Accordingly, by the system people can acquire professional help at anytime from anywhere.

According the above requirement, some researches proposes a mobile care system integrated with a variety of vital-sign monitoring, where all the front-end vital-sign measuring devices are portable and have the ability of short-range wireless communication. In order to make the system more suitable for sport IoTs applications, the technology of wireless sensor network is introduced to transmit the captured vital signs to the residential gateway by means of multi-hop relay. Then the residential gateway uploads data to the central servers via wireless Internet to carry out person's condition monitoring and the management of physiological data. Furthermore, the system is added in the alarm mechanism, which the portable monitoring device is able to immediately perceive the critical condition of the people and to send a warning message to the coaches and doctors in order to achieve the goal of instant response for the athlete condition.

In the recent research, Blood oxygen saturation is one of the key parameters to be monitored which assesses the percentage of arterial hemoglobine that is saturated with oxygen. Transmission and reflectance are two non-invasive techniques to perform pulse oximetry (SpO_2). Currently, the blood oxygen saturation is monitored by a transmissive pulse oximeter with the sensor attached on the foot or palm of the neonate [1]. Placement of these sensors and the presence of all the wires lead to discomfort and even painful stimuli when the sticky sensors have to be removed [2]. Reflectance pulse oximeters attached on forehead [3,4] have been developed. To optimize functionality and become wearable, the design of a monitoring system is essential, which integrates all technical components into suitable material and forms, as well as moves sensors to an invisible background for better the athlete wearing in the sport IoTs. Heart rate (HR) is another physiological parameter commonly used by sport IoTs monitoring systems [5]. It allows an assessment of the condition of the athlete, the cardiac arrhythmias can be recorded promptly and variations can be easily differentiated from normal/abnormal. This parameter was frequently used in studies and research projects, providing vital information on the cardiovascular function. HR is usually performed with devices that use the photoelectric plethysmography measurement method on peripheral arteries.

In the recent years, with the development of the integrated circuits technology, wireless networks, and medical sensors have opened the way to miniature, low power, and intelligent monitoring pulse oximeters, suitable for many portable sport IoTs wearable applications. It is a notable increase in the types and numbers of pulse oximeters, ranging from simple HR monitors to wireless digital pulse oximeters. Although these devices are used to the greatest extent, they are not suitable for portable monitoring due to their power supply and big bulk [5]. In order to monitor the athletes' SpO_2 and HR as a kind of portable method, wireless communication technology are employed for remote sport monitoring, giving him the freedom of movement [6].

The SpO_2 and HR are continuously measured by the proposed wireless systems using commercially available pulse oximeters. The results of measurements may be wirelessly transmitted to central monitoring station by using wireless sensor networks (WSNs), wireless mesh networks (WMNs), Bluetooth, WiFi and cellular networks. Meglinski et al. [7] proposed a simulation skin model, which comprises of water, HbO_2, Hb and hemoglobin-water free tissues, to calculate the oxygen saturation of the blood by the varied reflectivity of human skin in visible and nearinfrared spectral region. Tsai et al. [8] presented a method using the LED light sources at two different wavelengths to irradiate on the skin and construct the oxygen saturation image of shallow tissue. The results show the SpO_2 of human skin tissue which calculated from the reflected images illuminated by 660/890 nm lights were more close to the result obtained from multi-spectral imaging method than illuminated by 660/940 nm lights. the respiratory rate (RR) and HR would increase simultaneously during several minutes exercise. Hence, the alveolar oxygen tension will increase, but the arterial oxygen saturation will decrease because of the limiting diffusion of the lung. The value was 67 % at the rest situation falls into less than 50 % during severe exercise [9]. In addition, Miura et al. [10] employed a NIR imaging device to investigate the NIR-O_2 saturation and NIR-blood volume variation of the muscle at rest, during and after exercise. Their results show the NIR-O_2 saturation and NIR-blood volume decreased from the rest to a 2 minutes exercise, but the value increased when after the exercise to a 3 minutes recovery.

In [11], the authors combine research in textiles materials, and wireless sensor and actuator networks in the context of human body monitoring with statistical methods for the data analysis and treatment. Besides, they provide a hierarchical communication system that allows the delivery of the data collected from the garment. For monitoring team sports, the authors in [12] propose a novel mobility model. In this paper, the definition of specific interaction rules between team players is of primary importance to obtain accurate mobility patterns. The comparison with real mobility tracks highlights the need for a more accurate modeling of players' behavior.

In this paper we will adopt near-infrared portable tissue oximeter with detection module using STM32 microprocessor. Continuous-wave spectrometers are the most commonly used devices, which provide semi-quantitative changes in oxygenated and deoxygenated hemoglobin in small blood vessels (arterioles, capillaries and venules). Through the measurement using the near-infrared technology, we could obtain the blood oxygen saturation and the heart rate parameters. After obtaining the above two parameters, the portable device will send the data to the remote coaches or doctors via GPRS/WiFi/Zigbee netwokes. The data of the blood oxygen saturation and the heart rate that is detected by the detection module are processed by the expert decision-making system in order to provide the coaches and doctors with the athlete condition. In addition, the data can be sent to the smart phones of the players, coaches or doctors through GPRS/WiFi networks, in which the blood oxygen saturation and the pulse data of the athletes can be displayed according to the requirement of the remote users.

The paper is organized as follows. Section II presents the system architecture of the blood oxygen saturation and heart rate measurement system. In section III we provide the details about monitoring system. In section IV performance evaluation of this system is performed. Finally, Section V draws conclusions.

2. System architecture of the blood oxygen saturation and pulse measurement device

In this paper, we propose a system design of a real-time, wearable reflectance pulse oximetry based on a wireless sport IoTs networks. In order to monitor people physiological signals continuously, wearable reflectance pulse oximetry is built in the wrist form that could used to obtain oxygen saturation of the athlete unobtrusively. The wearable reflectance pulse oximetry consists of reflectance probe, SpO_2 module and wireless sport IoTs networks. The reflectance probe is designed to collaborate with two LEDs with wavelengths of 660nm and 940nm. SpO_2 module is designed to manage almost of all of the internal processing (e.g. analog signal processing, signal collection and calibration, etc). It is based on a low-power STM32 microcontroller that operates in 3.3V. Low-power processing SpO_2 module works together with wireless communication networks. The collected data from oxygen saturation and heart rate are transmitted wirelessly to a base-station for storage and analysis purposes. The system architecture is shown as follows.

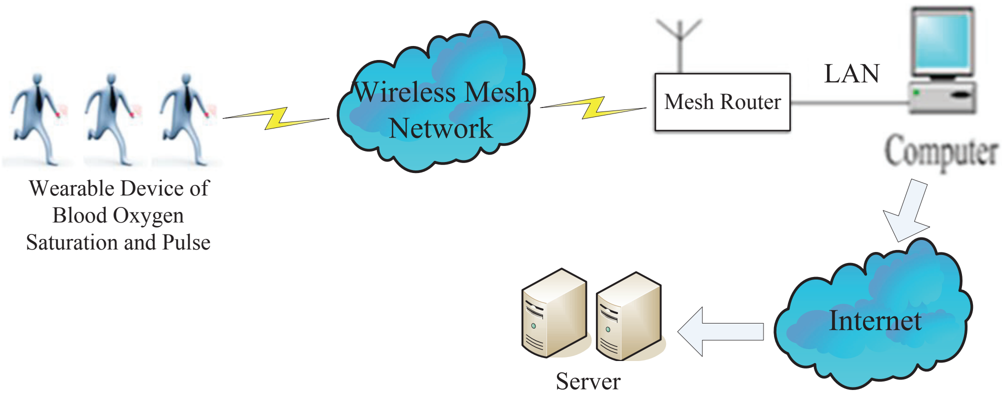


Fig. 1. System architecture of the total networks.

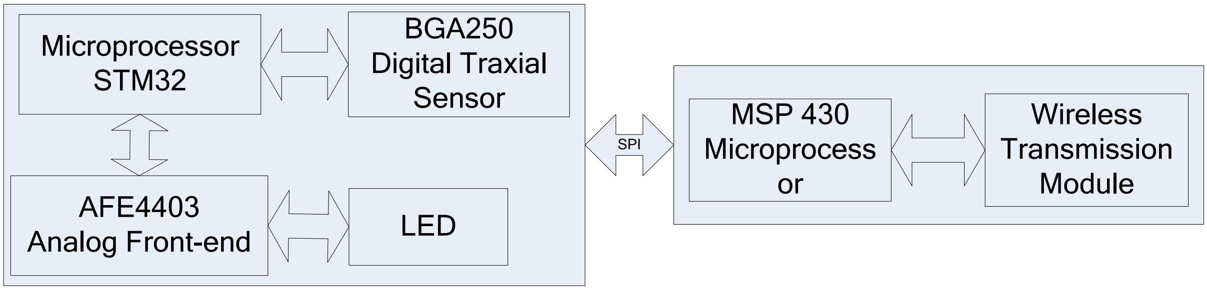


Fig. 2. System model of the blood oxygen saturation and pulse measurement device.

In the Fig 1, the system is composed of blood oxygen saturation and pulse measurement device putting on athletes, mesh nodes and routers, processing computer and central servers. For the blood oxygen saturation and pulse measurement device, it is mainly composed of physical information sensors, RF modules and microcontrollers, which can be put on athletes to monitor the working conditions of athletic tissues and organs (especially blood oxygen saturation and heart rate). These devices transmit gathering information to back-end servers to process through the converging mesh nodes. The transmission of information is consistent with IEEE 802.15.4 protocols, which by the means of multiple hops to transmit information. At processing computer, mesh router nodes are responsible for converging information coming from wireless networks, A/D conversing RF information using high-performance of controller chips, and then undertaking of down conversion. Finally, processed information is put into computers via LAN port. At the same time, computers can be regarded as human-machine interfaces, and working personnel can monitor various physical indexes of athletes by watching specified software. As soon as abnormity of the persons occur, persons are forbidden from the current sports and remedy works can be undertaken. Consequently, incidents of sudden death during the sports can be effectively avoided.

In the Fig 2, the measurement device for the blood oxygen saturation and heart rate provides athletes' the physiological parameters on the hardware platform. The measurement device uses the analog front end (AFE4403 chip) in order to obtain person blood oxygen saturation and heart rate using LED skin reflection signal. At the same time the measurement module uses a BMA250 for motion detection. BMA250 is a digital output of the three-axis accelerometer with low power consumption. We use mixed signal processor STM32 to calculate the blood oxygen saturation and heart rate using LED reflection signal with motion detection signal. The microprocessor MSP430 is used to control the whole system. In addition, to meet the communication function, this device also uses the wireless transmission module, such as Bluetooth/ GPRS/WiFi/Zigbee communication module. Using the wireless transmission module could transmit user's blood oxygen saturation and heart rate information to the smart phones of the players, coaches or doctors for processing and analysis according to the requirement of the different users.

3. System design description

As we discussed in Part 2, in this part we will describe the system design of blood oxygen saturation and heart rate measurement system. For this system, we will give an introduction for detection subsystem part and wireless transmission subsystem part.

3.1. Detection subsystem for blood oxygen saturation and heart rate

For blood oxygen saturation and heart rate subsystem, Photoplethysmography (PPG) signal is an important non-invasive technique for measuring blood oxygen saturation and heart rate. PPG operates by observing the light absorption and scattering properties of the capillaries, affected by the composition of the blood and engorgement during the systole phase of the cardiac cycle. Consequently, both blood oxygen saturation and heart rate can be determined. Usually PPG operates in the reflective mode. Reflective PPG works by illuminating a bed of capillaries, typically with light in the infrared (IR) range due to its low absorption by tissue, before measuring how the back-scattered light is modulated by the blood. Some Researches have shown that a wrist reflective PPG sensor can be much more comfortable to wear and that the tissue around the wrist is capable of providing a suitably strong PPG signal.

To measure heart rate on a mobile athlete, a PPG sensor must be physically comfortable with low power consumption and have the ability to manage harsh sensing environments such as those introduced by electromagnetic interference (EMI) and increased temperature or humidity. Using blood high opacity and the great differences between tissues and blood transmission of light, through the photoelectric pulse sensor to obtain the pulse signal, after AD change, via digital analysis and processing of sampling data, we can realize the measurement of the human heart rate.

SpO_2 is defined as the ratio of the level oxygenated hemoglobin over the total hemoglobin level,

$$SpO_2 = \frac{H_bO_2}{\text{Total Hemoglobin}} \tag{1}$$

Because of different oxygenation level, the finger can absorb different amounts of light when blood is passing through it. We assume the obtained reflective optical signal is $s_0(t)$, whose spectrum function is $S_0(\omega)$, and $n_0(t)$ is Gaussian noise, whose spectrum function is N_0. The filter transmission function is $H(\omega)$. So the output of this filter is as follows,

$$r(t) = s_0(t) + n_0(t) \tag{2}$$

Using $S_0(\omega)$, we can express the time domain signal $s_0(t)$ as,

$$s_0(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} s_0(\omega)\, e^{j\omega t} d\omega = \frac{1}{2\pi}\int_{-\infty}^{+\infty} s(\omega) H(\omega)\, e^{j\omega t} d\omega \tag{3}$$

So at time t_0, the output of the filter is

$$r_0(t) = \frac{|s_0(t_0)|^2}{N_0} = \frac{\frac{1}{2\pi}\int_{-\infty}^{+\infty} s(\omega)H(\omega)e^{j\omega t}d\omega}{\frac{n_0}{4\pi}\int_{-\infty}^{+\infty}|H(\omega)|^2 d\omega} \tag{4}$$

So we can obtain,

$$H(\omega) = kS^*(\omega)e^{-j\omega t_0} \tag{5}$$

where k is constant, and usually k can be equal to 1. $S^*(\omega)$ is conjugate spectrum of $s(\omega)$. So we can get its expression in time domain as follows.

$$h(t) = Ks(t_0 - t) \tag{6}$$

The skin reflection optical signal can be calculated by the convolution of $s_0(t)$ and h(t).

3.2. Wireless transmission subsystem

For the wireless transmission sub-system, it is used to transmit the data collected by the device of blood oxygen saturation and heart rate over short distances. This sub-system adopts some kind of microprocessoras a core processor of the frontend physical data gathering nodes. Usually we can adopt wireless sensor networks (WSNs), Mesh networks, Bluetooth or GRPS to finish the data transmission. For WSNs, we use ATmega128L as a core processor. It is a low power consumption CMOS chip based on AVR core with 128KB flash memory and 4KB EEPROM memory. It has general extension interfaces, which can be used to install various sensors to obtain the data, for example, the above data of blood oxygen saturation and heart rate. RF parts adopt CC2420 RF chips, which is a RF transmitter-receiver that works at 2.4GHz frequency band, can work at 19.7mA low power consumption, and has the high receiver sensitivity of -94dBm and good anti-jamming capability. The systematical structure and the PCB board of wireless sensor network node are depicted in Fig. 3 and Fig. 4, respectively.

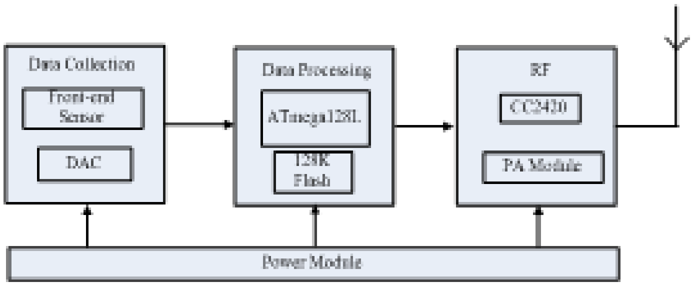


Fig. 3. Systematical structure of wireless sensor networks.

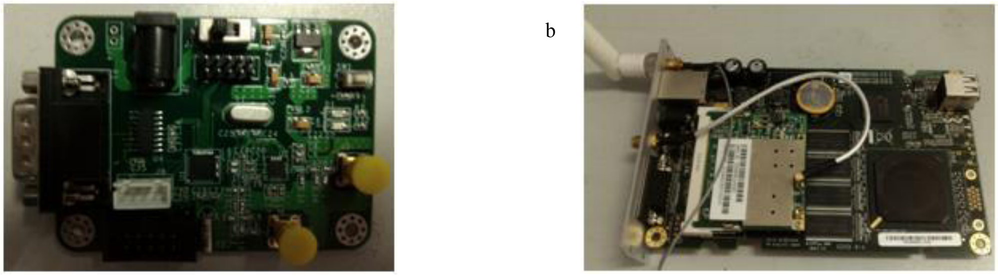
a b


Fig. 4. (a)WSN node board; (b) WSN node PCB board.

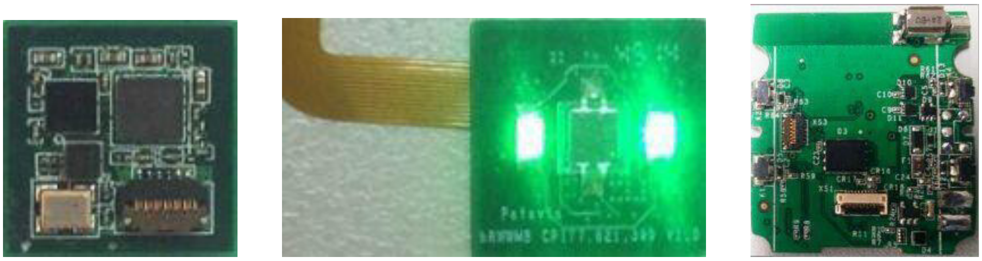
WSN gateway nodes are the systematical centers of controlling and processing with abilities of route maintenance, data process, and operation management. Compared with front-end sensor nodes, gateway nodes require high processing ability and operating speed. Hence, to realize high performance gateway nodes, general ARM is used, and gateway nodes are connected through general interfaces. In data gathering nodes and gateway nodes, we adopt TinyOS operating system to implement system design and develop various hardware drivers and applications according to their different hardware structures and functional requirements. TinyOS operating system is a complete, multiple-task, multiple-thread real-time operating system with the merits of open-source code, easy transplanting and development.

For the wireless mesh networks, it is used to transmit the message from WSN nodes over long distances. It adopts AMD CPU at 500MHz, 256MB DDR SDRAM, 2 miniPCI sockets for 802.11 wireless cards and other expansions. In addition, wireless module adopts Atheros IC, which supports 802.11 a/b/g/n protocols. The appearance of the wireless mesh router is shown in Fig. 4(b). In the wireless mesh router, software platform is based on open source Linux system with OLSR routing protocol. We achieved the hybrid networking at 2.4GHz and 5.2GHz frequency bands. The PCB board of wireless mesh networking node is shown in Fig. 4(b).

4. System implementation

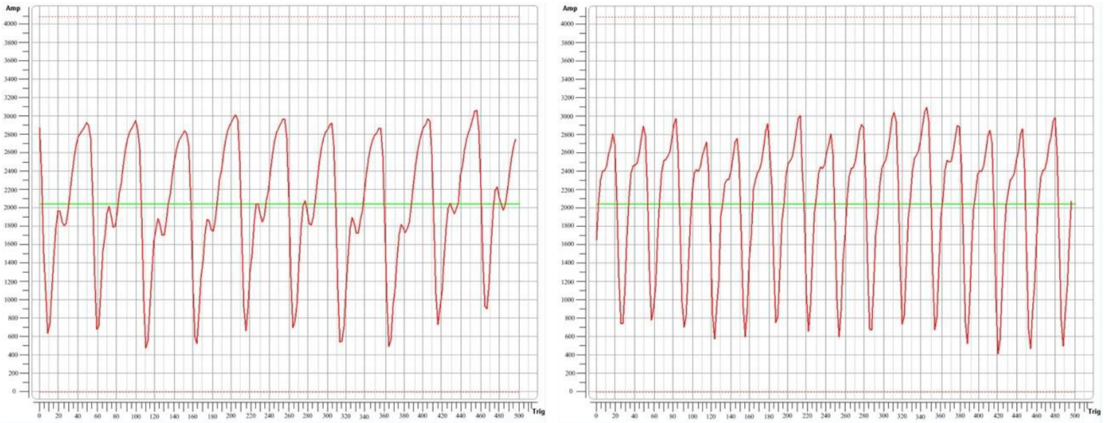
In this section, we present the system implementation. In the Fig 5, we finish the hardware design of this device. Fig 5(a) is a picture of detection board, in which we can see there are a stm32 microprocessor, G-sensor, analog front-end and connector. In fig 5(b), it is a working detection board, in which green LEDs will contact with the wrist. In fig 5(c), it is a mainboard to control the whole device, in which there a MSP430 microprocessor to handle all the events.

Fig. 6 shows the PPG curves before and after the sport. In the figures, X axis means time units and Y axis means normalized amplitude of PPG. From the PPG signal, we can obtain the SpO_2 value and heart rate. For the Fig. 6(a), we can measure the heart rate is 79 and SpO2 is 97. And from the Fig. 6(b), we can get the above values are 127 and 98, respectively.



a b c

Fig. 5. Detection board and mainboard of the device. (a) Detection board; (b) Detection board with power; (c) Mainboard.



a b

Fig. 6. PPG curves (a) before and (b) after the sport.

Table 1 shows us medical test device is compared with the existing device and our device. From this table, we can see there are two test scenarios, treadmill running and general running. For treadmill running scenario, we adopt three types of speed, which is 5km/h, 10km/h and 13km/h. For general running scenario, we adopt shuttle running of 30m round trip for 1 time and 5 times. For the existing device, we use the Philips watch, which has the best performance currently and is authorized to several companies, such as NIKE, MIO, Samsung, etc. From this table, we can obtain that our device's performance is better than the existing device.

Table 1. The heart rate test comparison of existing device and our device.

Test Modes	Speed (Km/h)	Medical Device	Existing Device		Our Device	
		Test Value	Test Value	Deviation	Test Value	Deviation
Treadmill	5	116	114	1.72%	116	0.00%
	10	158	155	1.90%	158	0.00%
	13	177	174	1.69%	175	1.12%
Running	One time 30m shuttle run (30m in total)	117	98	16.24	117	0.00%
	Five times 30m shuttle run (150m in total)	134	133	0.75%	133	0.75%

5. Conclusions

In this paper, we propose a near-infrared wearable device for the blood oxygen saturation and heart rate using microprocessors in sport IoTs networks. Through the measurement using the near-infrared technology, we could obtain the blood oxygen saturation and the pulse parameters. After obtaining the two parameters, the portable device will send the data to the remote coaches or doctors via GPRS/WiFi/Zigbee networks. The data of the blood oxygen saturation and the pulse that is detected by the detection module are processed by the expert decision-making system in order to provide the coaches and doctors with the athlete condition. In addition, the data can be sent to the smart phones of the players, coaches or doctors through GPRS/WiFi networks, in which the blood oxygen saturation and the pulse data of the athletes can be displayed according to the requirement of the remote users. The test results show that the accuracy of measurement is high and the system is stable.

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