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Article

Cardiac function monitoring during marathon training based on smart medical wearable sensor device

Hongjuan Cai, Miao Cai*

College of Information Science and Engineering, Wuchang Shouyi University, Wuhan 430064, Hubei, China
*** Corresponding author:** Miao Cai, caimiao0906@163.com

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Abstract: In recent years, intelligent wearable sensor devices have developed rapidly and can be seen everywhere in daily life. With the rapid development of electronic components and the continuous improvement of their performance, intelligent wearable intelligent products have gradually become possible and have shown explosive growth. In addition, intelligent wearable electronic devices have many advantages that traditional devices do not have. With the popularity of fitness wearable devices, intelligent wearable devices can also be used for real-time heart rate and dynamic electrocardiogram (ECG) monitoring during marathon sports. It can effectively prevent sudden death. During marathon training and other health services, it is very important to use intelligent wearable sensor devices to monitor heart function. This paper puts forward a heart function monitoring system for marathon training based on intelligent wearable sensor, expounds the origin of marathon sports and the importance of heart function monitoring for marathon athletes during training. This paper discusses the technology and construction method of heart rate monitoring system based on intelligent wearable sensor device. At the same time, relevant experiments are carried out to verify the relevant performance of the intelligent wearable sensor device in the algorithm. The results show that the *R* wave detection accuracy of wearable devices based on traditional algorithms is usually between 92% and 93%. The *R* wave detection accuracy of the intelligent wearable sensor device improved by the algorithm in this paper has been improved to more than 97%, and the *R* wave detection accuracy of the algorithm in this paper is much higher than that of the traditional algorithm. This also reflects the effectiveness of the intelligent wearable sensor device of the algorithm during the training of marathon athletes.

Keywords: heart rate monitoring; marathon races; wearable sensor devices; sensor nodes

1. Introduction

With the continuous improvement of public health awareness, marathon projects have also been widely promoted, which can also play a good role in promoting social and economic development and urban planning and construction. However, due to the excessive amount of exercise in marathon events, it is easy to cause athletes' heart rate changes quickly, and then sudden death. Therefore, wearable devices related to heart monitoring have come into being. With the continuous advancement of science and technology, wearable sensor devices have also developed rapidly, and wearable devices have become more and more diversified. Among them, health-related research has gradually become the key to smart wearable products. During the training process of marathon athletes, the use of wearable devices with heart rate monitoring function can reasonably monitor the athlete's heart rate and dynamic electrocardiogram, which can effectively prevent sudden death.

The detection of heart rate is an important indicator to reflect the state of heart function, so the research on heart rate detection is also a field that many experts and scholars devote themselves to. At present, the main researches in this field are as follows. Khamitkar Sahana S. developed a heart rate monitoring system using the Internet of Things technology. The purpose is to detect the heartbeat of patients, so as to monitor the risk of heart attack and conduct regular examinations. The system can be embraced and combined as part of the telemedicine system. The data received from the heart rate module can be saved and viewed for further medical use. The results of the prototype device can be used in various clinical studies [1]. Chen Hongbin proposed a small ultra sensitive accelerometer for continuous monitoring of lung and heart sounds to assess the lung and heart status of patients. Compared with traditional medical instruments, sensor equipment provides rapid and highly sensitive detection of lung and heart sounds, which greatly helps to evaluate the lung and heart status of patients with pneumonia. The sensor provides a cost-effective alternative method for the diagnosis and prognosis of pneumonia, and has the potential for clinical and household health monitoring [2]. Mercuri Marco proposed a continuous wave Doppler radar, which works as a phase-locked loop in the phase demodulator configuration, and demonstrated non-contact vital sign monitoring in vivo. After simulation and technical testing, to verify the function and security of the proposed architecture, a practical setting was demonstrated on human volunteers. The respiratory and heart rate information was successfully retrieved from the radar baseband signal using wavelet independent component analysis [3]. These studies provide an important direction for heart rate monitoring and are of great significance for the development of medical treatment. For athletes, in order to effectively prevent sudden death, it is necessary to be able to monitor their heart rate in real time during exercise.

Smart wearable devices can meet the requirements of real-time monitoring, and can learn the heart rate of athletes in the process of sports in real time. At present, the research on wearable devices in heart rate monitoring is mainly as follows. Gillinov Stephen studied the accuracy of five kinds of optical heart rate monitors in monitoring cardiac function during various types of aerobic exercise. The accuracy of the wearable optical heart rate monitor varies with the type of exercise. It is the highest on the treadmill and the lowest on the elliptical training machine. When accurate heart rate measurement is required, a chest monitor with electrodes should be used [4]. Hernando David evaluated the consistency between HRV parameters obtained from respiratory rate series recorded by wearable devices and HRV parameters obtained from ECG during low to high intensity dynamic exercise. In the whole test, the consistency between respiratory rate series obtained from Polar equipment and ECG is very high, although the shorter the respiratory rate, the greater the difference [5]. He Wenwen proposed a robust heart rate monitoring scheme for different quasi periodic motions based on wrist type optical capacitance tomography. It includes dictionary learning of signal feature learning, human motion recognition and dictionary selection of current motion recognition, noise elimination based on sparse representation, and spectral peak tracking of heart rate related spectral peak tracking. His experiments on six common quasi periodic motions show that the proposed method is more robust than some of the most advanced methods for different motions [6]. Georgiou Konstantinos investigated whether wearable devices provided reliable and accurate measurements of classic heart rate variability parameters during rest and exercise. The results show that wearable devices may provide a promising alternative solution for measuring rate variability. However, it needs to use appropriate methods to conduct more robust research in terms of the number of subjects involved, acquisition and analysis techniques under non-stationary conditions [7]. These studies provide theoretical guidance for wearable devices to be used in heart rate monitoring during exercise.

In recent years, the marathon race in China has shown a rapid development trend, and the number of runners in the marathon race is also increasing, but the sudden death events that follow have also occurred from time to time. Therefore, how to take corresponding measures to effectively prevent sudden death in marathon events has become a problem that must be urgently addressed. Wearable devices are characterized by rapid access to information, instant information analysis and intelligent display, which can fill the serious shortage of manpower in the medical device industry. Sensors can be used to obtain the key physiological information of marathon runners, and further real-time analysis using integrated chips can more effectively assess the physical condition of marathon runners.

2. Methods of monitoring cardiac function during marathon training

(1) The Origin of Marathon and the Importance of Cardiac Function Monitoring during Training

In 500 BC, the war between Greece and Poland broke out, in which the Athenians won. The Athenian commander wanted the people in the city to know the good news of victory as soon as possible, so he sent the famous “Scud” soldiers out to convey the good news. He didn’t get a proper rest after returning from Sparta, and then he started the forty kilometer long run again. His physical function has been damaged. When he ran into Athens, he was out of breath, fell to the ground and died. Marathon, a sports event, was set up to commemorate the long-distance running of Ferdinand.

While the urban marathon is going on, the safety problem must also be paid great attention. In recent years, there has been news of sudden death of marathon runners. This has caused great adverse effects on the rapid development of the urban marathon, and caused irreparable losses to the organizers and competitors. Therefore, it seems particularly important to prevent sudden death that may occur during marathon training [8,9].

According to the investigation, more than 90% of the sudden sports death events come from sudden cardiac death. Usually, they participate in the marathon carelessly without comprehensive training, or they do not conform to the training standards, and increase the amount of activity and intensity unscientific, which would lead to sports related sudden death [10]. Too high exercise intensity is an important reason for sports sudden death. Therefore, the bull’s-eye rate should be controlled during normal training. With the rise of intelligent wearable devices, it is also possible to use real-time heart rate and dynamic ECG in intelligent wearable devices to monitor exercise intensity and prevent sudden death during marathon training.

(2) Related concepts of wearable devices

Wearable devices refer to the electronic devices that can be worn on the body by integrating various sensors, communication technology, modern information technology, etc., and can realize the collection, recording and analysis of body statistical data. There are many kinds of intelligent wearable devices. In essence, all electronic devices that can be worn or adhered to human body can be called intelligent wearable devices [11,12]. According to different types of adhesive parts, intelligent wearable devices can be divided into multiple types. For example, there are watches, smart wristbands, wrist bands and other wearables worn on the inside of the wrist, rings and rings worn on the ring, glasses, hats, masks and other wearables worn on the head, smart running shoes worn on the feet, and clothes worn on the body. In addition, there are smart bags and smart crutches, which are also popular new electronic devices [13–15].

Cardiovascular health wearable devices can also be divided into smart bracelets, wrist bands, binding bands, trouser bands, foot rings, skin patches, etc. according to different wearing parts and methods. According to different acquisition methods, it can be divided into continuous, interrupt, real-time and other acquisition devices. According to the difference of sensors, it can be divided into biological current sensor equipment, infrared sensor equipment, mechanical equipment, electric sensor equipment, etc.

When athletes are tired, they would cause the change trend of the relationship between heart rate and running speed, which can give corresponding basis for the prevention of sudden death in marathon competitions. In addition, it is also an important factor to predict and analyze the sudden death of body-building sports by using the waveform replacement pattern to carry out the ECG test of athletes. The abnormal phenomenon of central visceral repolarization after recovery has a strong correlation with sudden death, so it can also be used as an important prediction and analysis parameter of sudden death.

(3) Sensor related concepts

Sensor is a kind of information acquisition equipment that is often necessary in contemporary mechatronics machine equipment [16,17]. The basic function of sensor is to perceive the external information content and convert it into a signal that can be solved for subsequent system control. The actual principle of different sensors is related to their types. For example, the principle of thermistor is that the resistance value of semiconductor material would change according to the change of external temperature. Therefore, by observing the working voltage at both ends of the thermistor, the temperature of the surrounding environment can be measured by the equivalent substitution method. For the light sensor, the principle of its use is mainly photoelectric effect. When a certain intensity of light shines on the photosensitive raw materials, electrons on the surface of the photosensitive workpiece would migrate, thus generating a certain working voltage. By checking the working voltage, the ambient light intensity can be measured by equivalent substitution method. Similar working pressure, offset and speed sensors use relevant physical conversion to complete the cognition of parameters. The electronic optical heart rate sensor irradiates light into human skin, perceives the change of color in blood, and then converts it into electronic signal through photoelectric sensor. This is photo plethys mographic (PPG for short) [18,19].

The photoelectric plethysmography heart rate measurement technology is a widely used method in the current market for various smart bracelets, watches and other wearable devices to detect pulse rate and heartbeat [20,21]. The pulse rate and heartbeat data provided by intelligent wearable devices have important guiding significance for the management of chronic diseases such as heart rate manipulation. In addition, wearable devices can detect the heart rhythm based on the technology of measuring heart rate by optical capacitance plethysmography, which can screen out more common arrhythmia.

(4) Cardiac function monitoring during marathon training based on wearable sensor device

In order to obtain the movement data of athletes during marathon training to detect their movement status, this paper designs a wearable sensor device motion monitoring system based on artificial intelligence technology. This system includes three subsystems: sensing, human-computer interaction and global network service. The overall architecture of the wearable device motion monitoring system is shown in **Figure 1**. The sensing subsystem is based on intelligent wearable sensing devices. The sensing equipment is equipped with a three-way instantaneous speed sensor, a microcontroller and a wireless antenna to collect motion data and then solve the problem. It identifies the movement status of marathon athletes during training to achieve statistical analysis of the amount of exercise, and then transmits the processed values to the intelligent mobile terminal according to low-power Bluetooth.

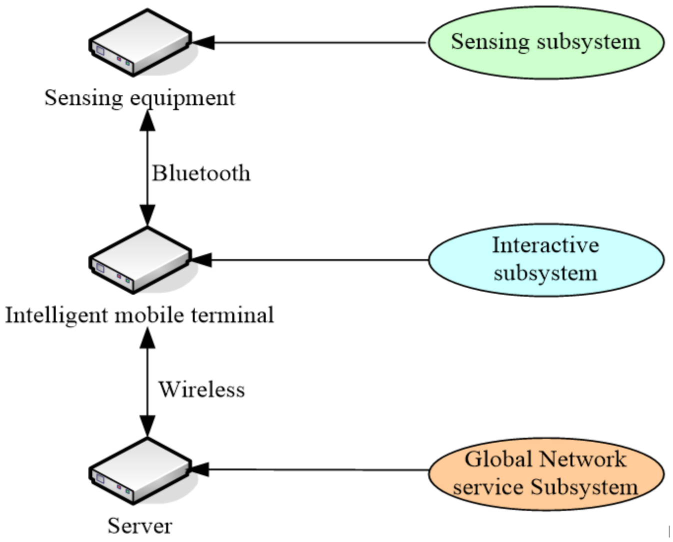

Figure 1. Overall architecture of wearable device motion monitoring system.

The development process of intelligent wearable device software is shown in **Figure 2**. First, after the intelligent wearable device is powered on, the six axis motion module starts to collect the acceleration, angular velocity and other data of marathon athletes at the set sampling frequency. The collected data can then be sent to the microprocessor. This paper uses a microprocessor to ensure that the sampling frequency can be kept at 100Hz. By using the received data, it finally obtains the generated acceleration, angular velocity and other information content, and then passes through a low-pass filter. The data processed in this way can be used to calculate the number of steps and the heat consumed by marathon athletes. During a running cycle, the generated acceleration would have a maximum value and a minimum value, so people can set an appropriate threshold range between the maximum and minimum values to determine whether to walk a step.

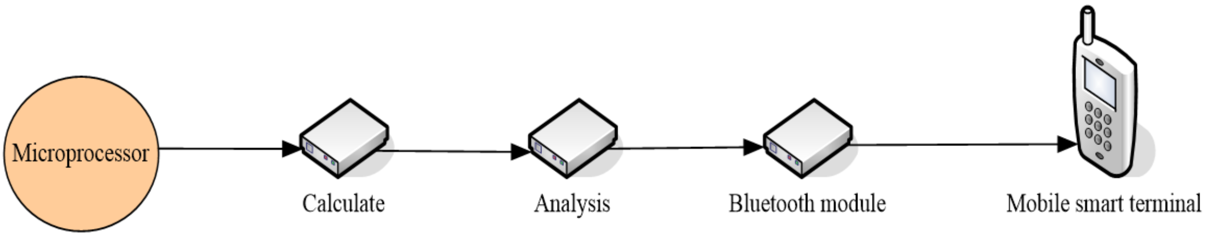

Figure 2. Development process of intelligent wearable device software.

The software of sensor node system is mainly composed of main program, interrupt program flow and system terminal program. The main tasks undertaken by the main program are initial setting, power consumption inspection, wireless connection creation, etc. The interrupt program flow is started by the sensor interrupt pin, which is mainly responsible for loading sensor data information and generating data files to be uploaded. The client program is mainly responsible for transmitting data packets to the supervisory host computer server according to the personalized communication protocol.

The main program of sensor node is shown in **Figure 3**. After the main program is powered on, the initial setting is carried out first, and then the power consumption inspection of the connection point is carried out. It then starts to scan the wireless data signal and create a connection with the data information wireless relay. When the connection is completed, it starts to collect sensor data.

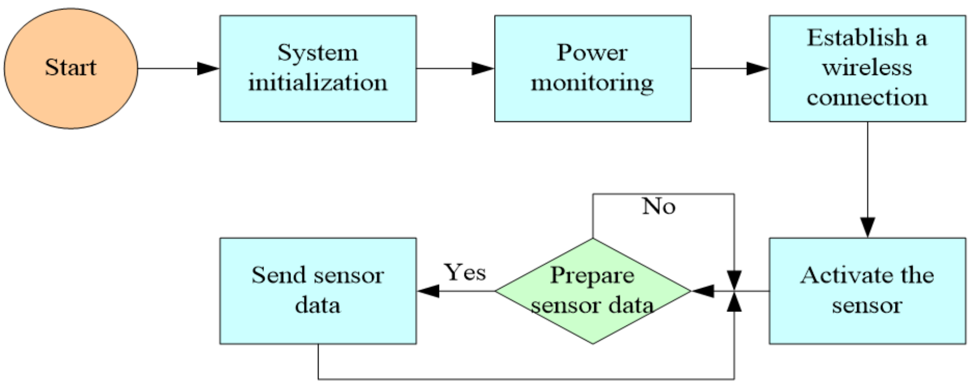

Figure 3. Main program flow chart of sensor node.

The interrupt service program flow chart is shown in **Figure 4**. The time interval for the interrupt program flow to be started by the sensor is 10ms. The CPU loads the sensor data information in the interrupt system, and packs the data into the buffer area every 500ms. After the main program detects that the data files in the buffer area have been prepared in advance, it would enable the client program to send the data information to the network server of the monitoring host computer.

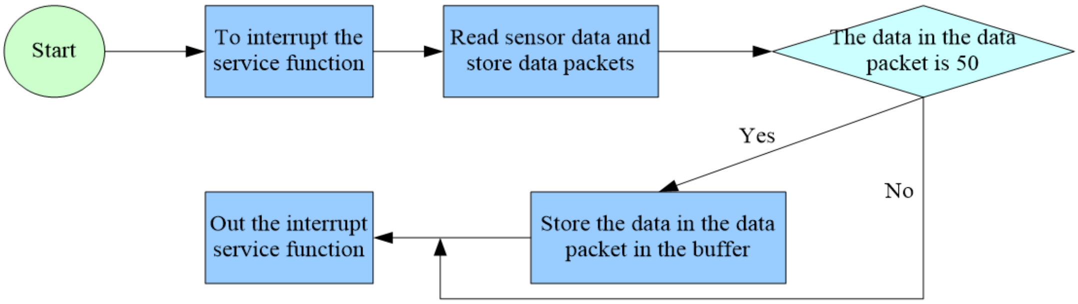

Figure 4. Interrupt service program flow chart.

The client program creates a connection with the monitoring host computer network server according to the socket protocol network communication mode and the preset Internet protocol address information server port. After the connection is created, the system client can share data with the server by pushing and accepting function formulas.

This paper proposed a wearable sensing device based cardiac function monitoring during marathon training, which involves the following formula:

$$ACC_x = SQRL(ACC_x a^2 + ACC_x b^2 + ACC_x s^2 \tag{1}$$

ACC_x-Synthetic acceleration of marathon athletes

$$ANG_w = SQRL(ANG_x wa^2 + ANG_x w^2 b + ANG_x w^2 s) \tag{2}$$

ANG_w-Synthetic angular speed of marathon athletes

$$RQ_x = H_x \cdot \sqrt[4]{V_{max} - V_{min}} \tag{3}$$

RQ_x-Step estimation, V_{max}- peak value, V_{min}-valley value, H_x- athlete's height

$$N_x = [(RU_{max} - URU) \times G] + RU_{res} \tag{4}$$

N_x-Marathon runner's bull's-eye rate, G-exercise volume, RU_{max}- maximum heart rate, URU- resting heart rate

$$N_x = [(PRU_{max} - URU) \times G] + URU \tag{5}$$

PRU_{max}-Second order heart rate, URU- resting heart rate.

3. Cardiac function monitoring experiment during marathon training

Intelligent wearable device concept:

Intelligent wearable devices are the general name of wearable devices, such as watches, bracelets, glasses, clothing, etc., which are designed intelligently for daily wear by using wearable technology. The wearable intelligent device has a long history of development. The idea and prototype appeared in the 1960s, while the device with wearable intelligent device form appeared in the 1970s and 1980s.

In order to effectively prevent the sudden death of marathon athletes in the process of sports, and timely adjust the sports state through heart rate monitoring, this paper proposes a wearable sensing device based cardiac function monitoring during marathon training, and real-time monitoring of athletes' heart rate during marathon training through wearable devices. In order to test the effectiveness of wearable devices, this paper conducts relevant experiments to verify their performance. Through communication and coordination, this paper selected 8 male participants who had participated in marathon in one city. The eight runners expressed their willingness to cooperate in this test. The physical fitness of the eight runners was not much different, which effectively guaranteed the validity of the experimental results. They wore wearable devices on their hands and performed different tests according to the instructions in this article. All tests were conducted on the treadmill. The relevant experimental results are as follows:

In ECG, *R* wave is a part of the whole process wave group of ventricular depolarization, and belongs to one of the ventricular depolarization waveforms. The accuracy rate of *R* wave detection of wearable devices is an important parameter to reflect whether it is effective to monitor the heart function of marathon athletes during training.

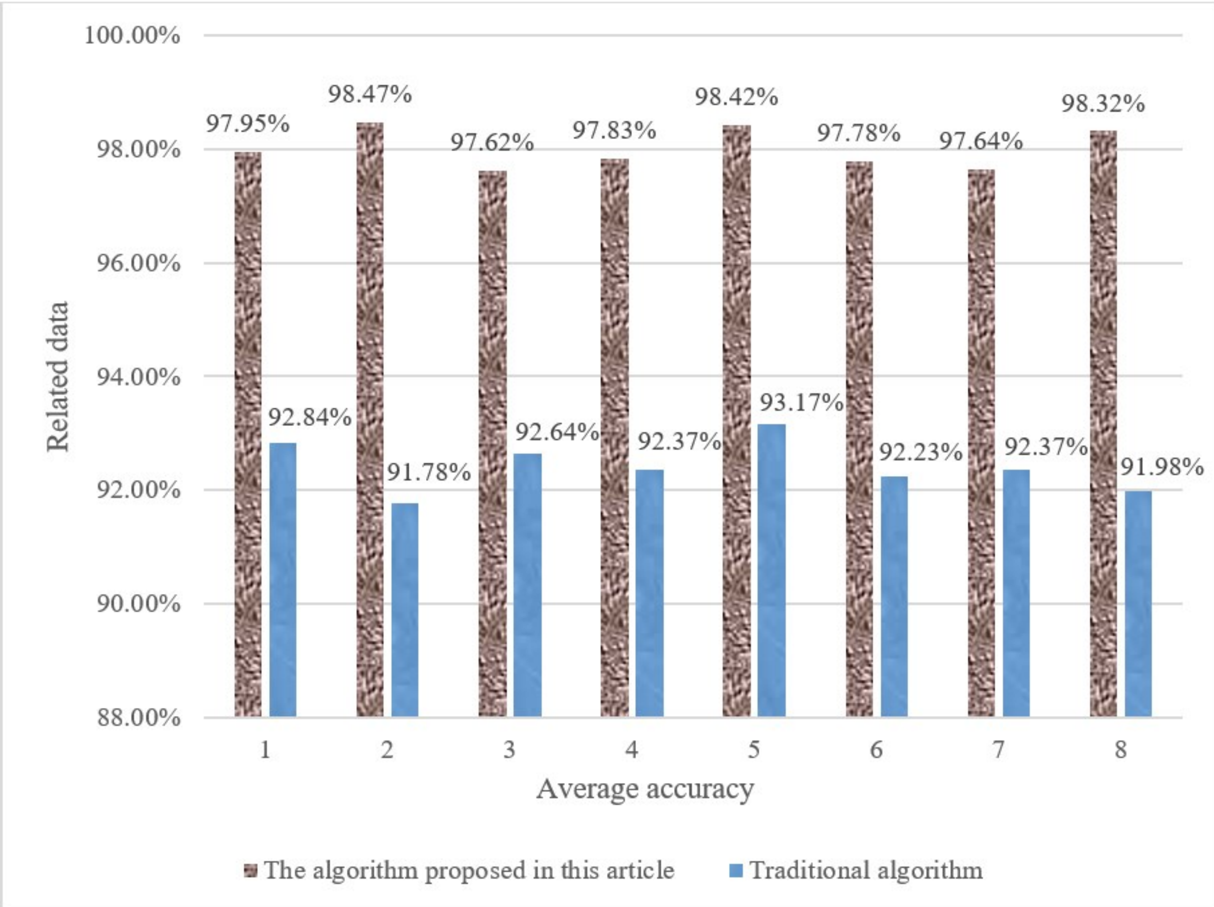

Figure 5. Accuracy of *R* wave detection for wearable devices with improved algorithm and traditional algorithm.

Eight testers wore the wearable device based on the algorithm in this paper and the traditional wearable device on their left and right hands respectively, and performed 3 km running training on a treadmill according to the usual training standards. Then this paper monitored their exercise data information, obtained the number of *R* waves during their exercise, and compared it with the actual number of *R* waves of the subjects to detect the *R* wave detection accuracy of the wearable device based on the traditional algorithm and the *R* wave detection accuracy of the improved algorithm in this paper. **Figure 5** shows the statistical chart of *R* wave detection accuracy of wearable devices with improved algorithm and traditional algorithm. It can be seen that the accuracy of *R* wave detection of wearable devices based on traditional algorithms is generally maintained at 92%–93%. The accuracy rate of *R* wave detection of wearable devices improved by the algorithm in this paper has been improved to more than 97%. For these 8 subjects, the highest accuracy rate is 98.47%. Compared with the traditional algorithm, the accuracy of this algorithm for *R* wave is much higher. The accuracy of the improved algorithm for *R* wave detection also reflects the effectiveness of the wearable device of this algorithm for athletes during training.

The accuracy of wearable devices for marathon athletes' step detection during training is also an important parameter reflecting their performance. For marathon runners, long time and long distance running is very costly for their bodies. Therefore, a scientific training method is required during the training process, and the accuracy of wearable devices for pace detection would be very important.

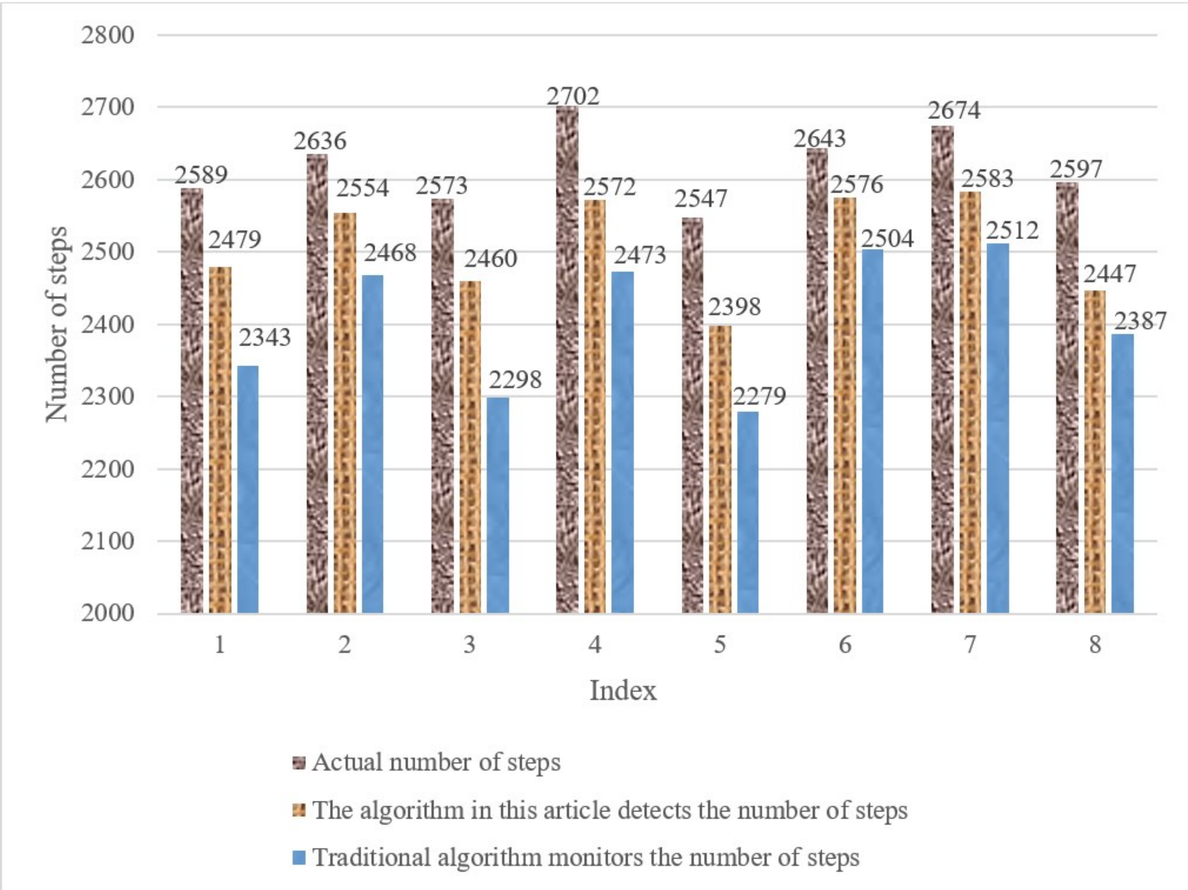

Figure 6. Comparison of detection steps and actual steps.

Figure 6 is a statistical comparison of the number of steps detected by the wearable device and the actual number of steps of the proposed algorithm and the traditional algorithm. The horizontal axis is the subject number and the vertical axis is the number of steps. It can be seen that both the proposed algorithm and the traditional algorithm detect that the number of steps of the subject during running is less than the actual number of steps. It can be seen that both the algorithm in this paper and the traditional algorithm detect the number of steps of the subjects in the process of running less than their actual running steps. In this paper, subject 1 is taken as an example. Its actual running steps are 2589, but the traditional algorithm only detects 2343 steps, while the algorithm in this paper detects 2479 steps, which is closer to the real value than the traditional algorithm. Generally speaking, the algorithm in this paper is closer to the real value than the traditional algorithm for the detection of the steps of the subjects in the movement process, which shows that the algorithm in this paper is still effective for the improvement and optimization of the traditional algorithm. The basic principle of wearable devices for step number detection is to detect the turbulence caused by the movement of the object's center of gravity to calculate the step number. From the experimental results, although this algorithm has improved the step detection accuracy compared with the traditional algorithm, there is still room for improvement, and more research is needed in this area in the future.

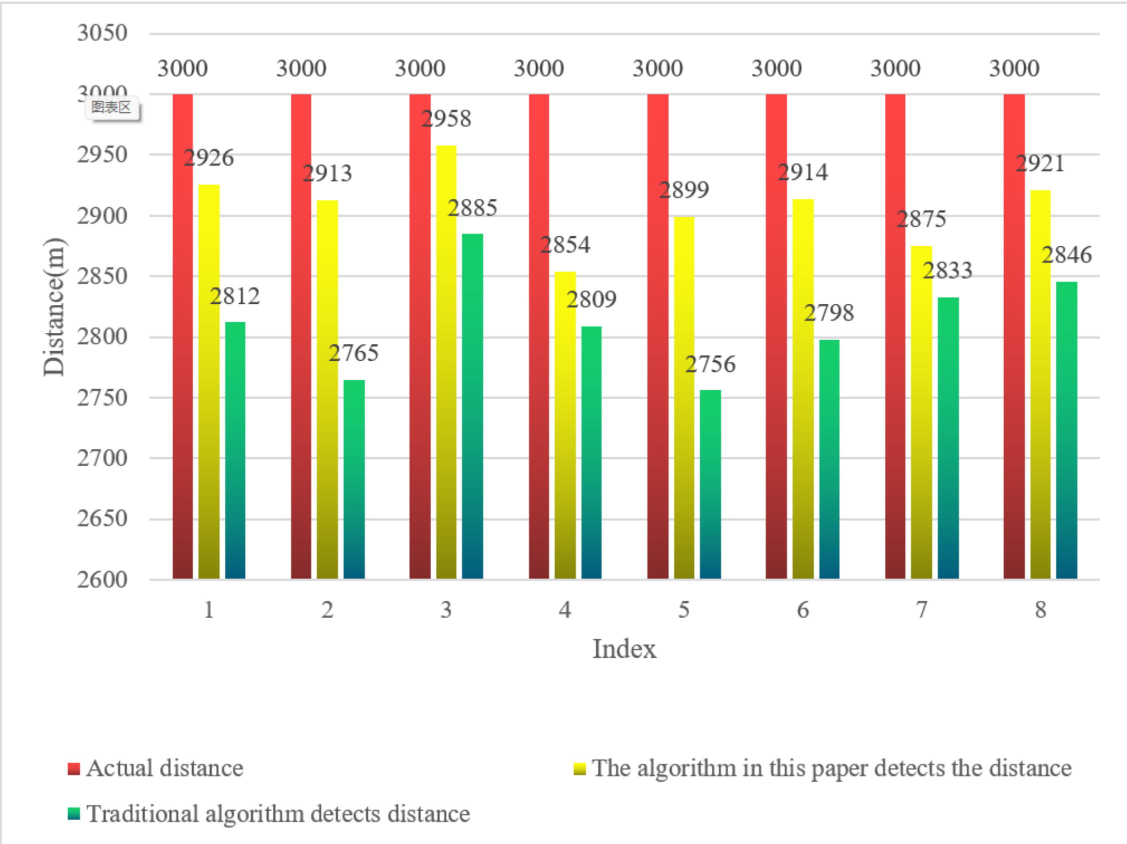

Figure 7. Comparison between detection distance and actual distance.

Figure 7 shows the statistical chart of the comparison between the detection distance and the actual distance of the wearable devices of the algorithm and the traditional algorithm. It can be seen that the test results are similar to the step number detection results. Whether the traditional algorithm or the wearable device of the algorithm in this paper, the detection of athletes' running distance is shorter than the actual distance. The reason is mainly due to the phenomenon of missing detection during the high-intensity sports training. However, it is worth mentioning that the algorithm in this paper is much higher than the traditional algorithm in detecting the moving distance of subjects. For the distance of 3000 m, the traditional algorithm generally detects the distance between 2750 m and 2850 m, and only one detection distance is 2885 m, which is the closest to the true value. In this algorithm, the maximum distance detection reaches 2958m, and the detection results of other subjects are much higher than the traditional algorithm. The exercise process of each person is different, so the detection results for the exercise process are also different. The detection accuracy may be higher for one subject, but lower for another subject. These are normal phenomena, and there is no wearable device on the market that can calculate accurately. With the continuous development of science and technology, relevant algorithms would continue to improve, and the accuracy of the athlete's steps and distance detection during training would also continue to improve.

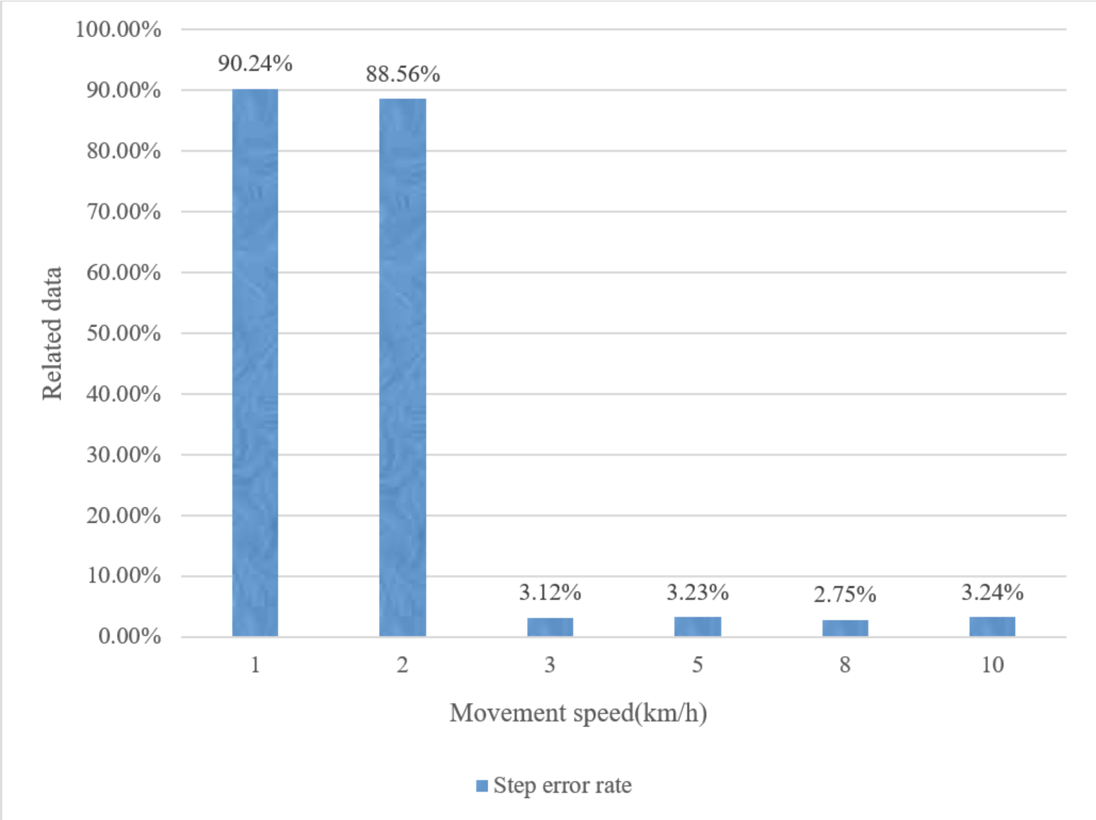

Figure 8. Relationship between step detection error rate and motion speed.

As shown in **Figure 8**, the statistical graph of the relationship between the error rate of step number detection and the movement speed of the subject during the exercise process is shown. It can be seen that the error rate of step detection reached 90.24% when the subjects were training at a pace of 1 km/h. The error rate of step number detection also reached 88.56% when training at the pace of 2 km/h, while the error rate of step number detection was 3.12%, 3.23%, 2.75% and 3.24% when the subjects were training at the pace of 3 km/h, 5 km/h, 8 km/h and 10 km/h. The error rate of step number detection has dropped a lot, which shows that the wearable device of the algorithm in this paper is more suitable for medium and high intensity training, and it also affects the accuracy of the step number and distance detection of the subject to a certain extent.

We summarize the performance of these two sensors in monitoring and make an overall comparison. The results are shown in **Table 1**:

Table 1. Performance comparison.

	Traditional sensors	**Smart sensors**
Accuracy	±7 BPM	±5 BPM
Real-time	1 time/s	2time/s
Battery life	3 days	7 days
Anti-interference	50 db	80 db

From the results, we can see that in terms of overall performance, the sensor's accuracy, real-time performance, anti-interference and battery life are better than traditional sensors.

4. Conclusions

This paper discusses the technology and construction methods of the heart rate monitoring system based on smart wearable sensors, and verifies the relevant performance of the smart wearable sensor device in the algorithm through experiments. The results show that the *R*-wave detection accuracy of wearable devices based on traditional algorithms is usually between 92% and 93%, while the algorithm proposed in this paper improves the *R*-wave detection accuracy to more than 97%. The shortcomings of this study are that only a limited number of subjects were experimented with, and the focus was mainly on the technical aspects of cardiac function monitoring. In the future, the number of subjects should be further expanded, a more robust research method should be adopted, and the personalized application of smart wearable devices in the functional monitoring of marathon training centers should be explored in depth to meet the diverse needs of athletes.

Author contributions: Conceptualization, HC and MC; methodology, MC; software, HC; validation, HC and MC; formal analysis, HC and MC. All authors have read and agreed to the published version of the manuscript.

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