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Heart Rate Demodulation System for BCG Signal Analysis

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Abstract: In order to achieve portable heart rate signal acquisition and analysis, and to benchmark the precision of electrocardiogram testing, a heart rate demodulation system based on fiber optic sensing is proposed. The heart impact signal of the tester is obtained through an FBG sensor, which is encapsulated in a flexible silicone sheet. The cardiac shock signal obtained from the test is used to invert the spectral shape of heart rate through the HRV algorithm. The calculation relationships of multiple parameters such as overall variability, short-term variability, and power spectral density were derived. The experimental test results show that quantitative analysis of JJ interval can effectively calculate heart rate values with an accuracy of ± 1bpm. It compared the distribution range of core parameters. Statistical analysis of test data can obtain a histogram of JJ intervals. From the distribution of the histogram, it can be seen that the test data has good stability. It validates the feasibility of this algorithm.

1. Introduction

Real time monitoring of heart rate is of great significance as it can effectively reflect the physiological state of the human body. The existing heart rate detection methods include electrocardiographs, heart rate wristbands, etc. The electrocardiogram machine has high testing accuracy, but it is expensive and has poor portability [1-4]. Heart rate wristbands are compact and convenient, but their testing accuracy is low and they cannot provide other heart rate status information beyond heart rate [5,6].

It is necessary to study a human physiological parameter monitoring system based on fiber optic sensing flexible measurement in order to reduce discomfort to the human body during the measurement process, increase the measurement sustainability and anti-interference ability [7]. At present, similar products both domestically and internationally are mainly used in electrocardiogram machines for hospitals. Although these devices have high measurement accuracy and good stability, they have complex structures, high costs, and a large instrument volume that is only suitable for use in fixed places such as wards, lacking flexibility. For patients with cardiovascular and pulmonary diseases who do not require hospitalization, or users for preventive monitoring, real-time monitoring is neither convenient to carry nor expensive [8-9]. For disposable ECG electrode patch products, their compact structure effectively solves the problem of convenient portability and measurement at any time. However, their measurement parameters are single, often only able to identify heart rate parameters, and their one-time use cannot be recycled, limiting their ability to measure and test multiple times [10]. In contrast, fiber optic sensing technology has the advantages of high flexibility, low cost, and high accuracy in testing heart rate.

The paper studies a portable wearable human physiological parameter monitoring system based on flexible sensing. The new FBG structure design achieves the testing goal of real-time flexible sensing, constructs a calculation model of sensing network test data and physiological parameters to achieve the quantitative analysis of human physiological parameters, and constructs a multi state correction database to improve system universality, making it suitable for general occasions where patients wear it at any time in their daily lives.

2. Analysis of BCG signal characteristics

The cardiac shock signal obtained by fiber optic sensing is BCG signal, which is a non-invasive monitoring method [11]. It uses the detection of the impact force generated by heart contraction, blood ejection, and blood flow deceleration, which can reflect the dynamic changes of blood flow to evaluate cardiovascular function. The principle of this technology is based on the small force generated by the blood entering the blood vessels every time the heart beats [12]. Using high-sensitivity fiber optic sensors to capture corresponding reaction force signals, and then using algorithms to analyze and calculate core indicators such as heart pumping efficiency, the BCG basic waveform is shown in Figure 1.

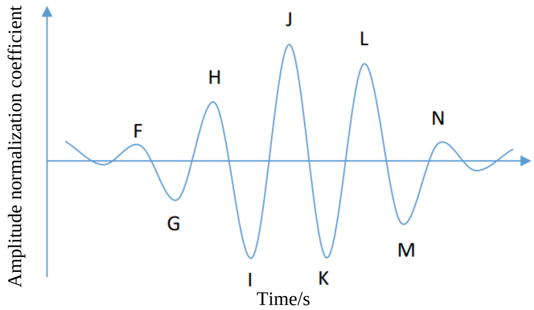

Figure 1 BCG signal waveform characteristics

Fiber optic sensing technology has high sensitivity, medical grade data accuracy, strong applicability, and anti-electromagnetic interference characteristics. It can accurately capture the pressure fluctuations of the mattress caused by blood flow when the subject is lying down. The pressure sensor embedded in it will convert the collected composite pressure signal into a digital time series through an AD converter, and then use drift compensation to eliminate baseline interference. Combined with digital filtering technology, it separates pure BCG waveforms from the original signal, and finally analyzes multiple dimensions of cardiac function parameters such as heart rate and vascular elasticity. The period between two peak values of J is called the JJ interval.

3. HRV algorithms for BCG

The measurement of Heart Rate Variability (HRV) in cardiac shock maps [13, 14] is based on the correlation between cardiac mechanical activity and the autonomic nervous system. It captures the whole-body vibration signals generated by cardiac ejection in a non-contact manner and analyzes the dynamic changes during the heartbeat interval. The core principle is that when the heart beats, the reaction force generated by the blood hitting large blood vessels will cause small vibrations throughout the body. After collecting the signal using piezoelectric sensors or accelerometers, signal processing algorithms are used to extract the characteristic points of the heartbeat, calculate the time interval between adjacent J peaks, and finally quantify the regulatory ability of the autonomic nervous system.

Time domain analysis directly calculates the volatility of JJ intervals [15], including: SDNN (overall variability):

$$SDNN = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(JJ_i - \overline{JJ})^2} \tag{1}$$

Reflecting the total tension of the autonomic nervous system [16], the normal range is 50-150ms, and a decrease suggests sympathetic hyperactivity or parasympathetic inhibition of RMSSD (short-term variability):

$$RMSSD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}(JJ_{i+1} - JJ_i)^2} \tag{2}$$

Healthy individuals typically have a risk of coronary heart disease above 10%, while those below 5% are significantly associated. Frequency domain analysis converts the JJ interval sequence into power spectral density (PSD) through Fourier transform, and divides the frequency band to quantify neural oscillations:

$$LF = \int_{0.04}^{0.15} P(f)df \tag{3}$$

Under the joint regulation of sympathetic and parasympathetic systems, standardized LF (LFn = LF / (TP - VLF)) reflects stress reflex sensitivity. Under stress, LFn increases, and its high-frequency power is:

$$HF = \int_{0.15}^{0.4} P(f)df \tag{4}$$

Used to evaluate sympathetic vagal balance, long-term>3 indicates the risk of chronic stress or heart failure. Nonlinear analysis uses Poincar é scatter plots to describe the chaotic characteristics of JJ interval sequences, and obtains SD1 (short-term variation) and SD2 (long-term trend) parameters through ellipse fitting. The decrease in SD1/SD2 ratio is associated with the deterioration of autonomic nervous function in patients with myocardial ischemia. In addition, the detrended fluctuation analysis (DFA) calculates the scaling index α, where α ≈ 1 represents the fractal characteristics of health, and a deviation of α from 1.0 indicates a pathological state.

4. Experiments

4.1. Experimental conditions

Real time heart rate acquisition testing is conducted for testers, using an electrocardiograph and fiber optic sensing system simultaneously. The system obtains BCG and ECG signals separately and completes the demodulation analysis of heart rate. The testing system is shown in Figure 2.

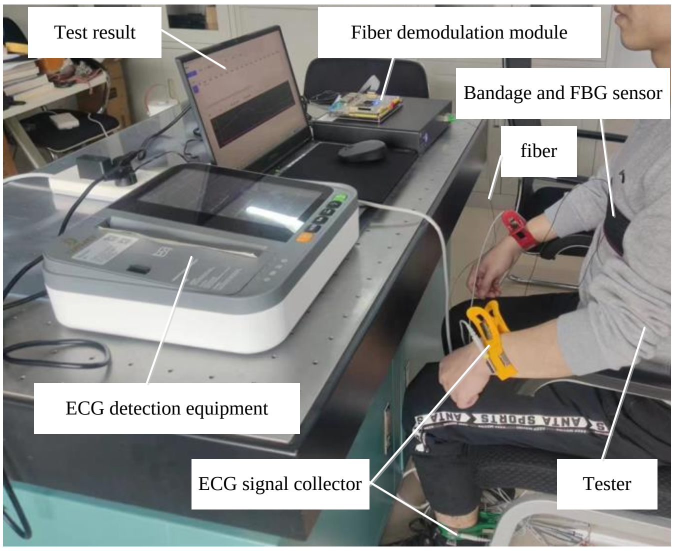

Figure 2 ECG and BCG signal acquisition experiment

4.2. Experimental data collection

Since the electrocardiograph is an integrated device that can directly calculate heart rate, it will not be elaborated here. The BCG signal is implemented by this system, and the test data and filtering curves are shown in Figure 3.

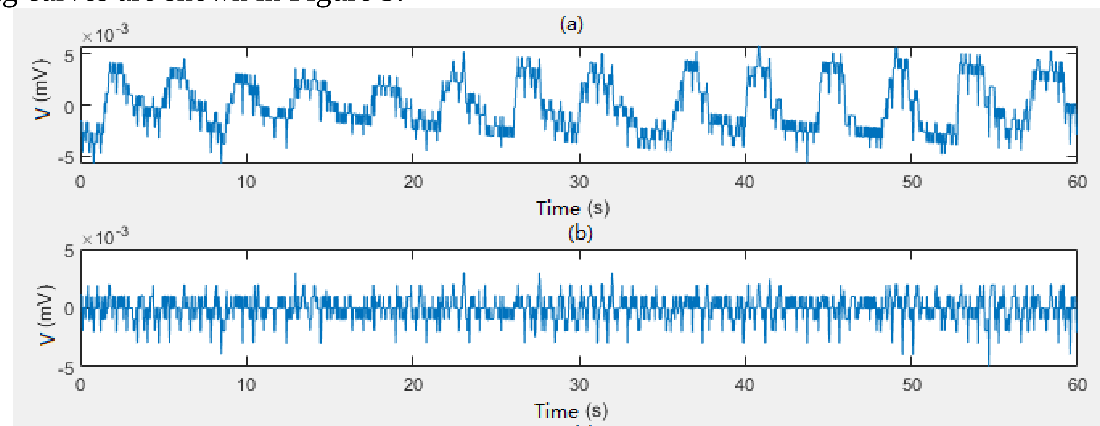

Figure 3 BCG raw signal and optimization processing

The raw data of heart rate is collected, and its signal waveform is shown in Figure 3 (a). It can be seen that the amplitude voltage during the heart rate fluctuation process fluctuates to some extent and is not completely consistent. Meanwhile, there are also certain differences in heart rate intervals. After extracting the original heart rate signal, its basic noise is shown in Figure 3 (b). The amplitude level of these signals can reflect the intensity of noise.

4.3. Experimental data analysis

Analyzing BCG signals using MATLAB. The accuracy of heart rate testing is ± 1bpm, and the waveform similarity is better than 80%. The system utilizes three core indicators: standard deviation (SDNN), root mean square deviation (RMSSD), and ratio of adjacent interval differences (pNN50).

The system first calculates the time-domain parameters using standardized formulas based on the input heartbeat interval sequence. SDNN reflects the overall variability of sympathetic parasympathetic nervous system synergy, with a normal range of 50-100ms. When it falls below 50ms, the system indicates impaired autonomic nervous system function. RMSSD is used to quantify the rapid regulatory ability of the parasympathetic nervous system and is highly correlated with respiratory sinus arrhythmia. Its threshold is set at 20ms, below which it means insufficient vagal tone. PNN50 counts the proportion of adjacent interval difference exceeding 50ms, and its critical value of 3% is used as the screening standard for diabetes autonomic neuropathy. The system can draw a scatter plot JJ interval sequence diagram, using the dynamic changes in heartbeat sequence numbers and interval values to identify premature beats or the process of motor recovery. The JJ interval test for the tester is shown in Figure 4.

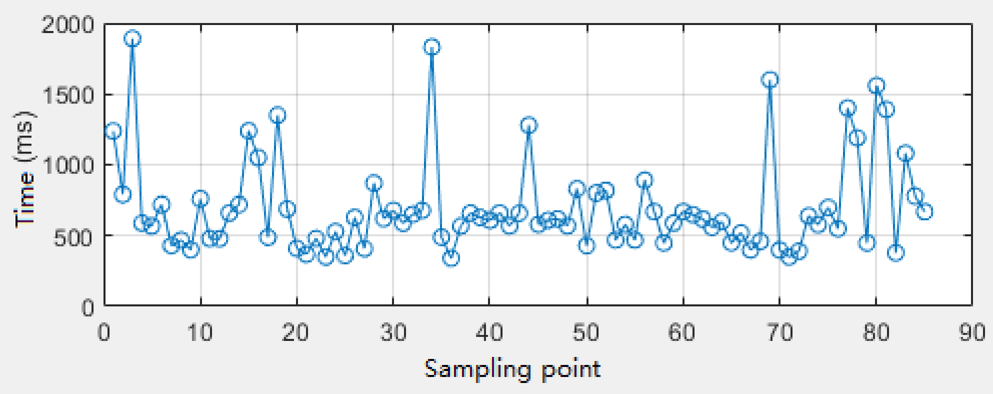

Figure 4 Time domain analysis of JJ interval

Normal sinus rhythm follows a unimodal approximately normal distribution, with a bimodal distribution suggesting atrioventricular block and a right-handed distribution associated with premature atrial contractions. As shown in Figure 4, the JJ interval between its main peaks can be observed to analyze the degree of heart rate change.

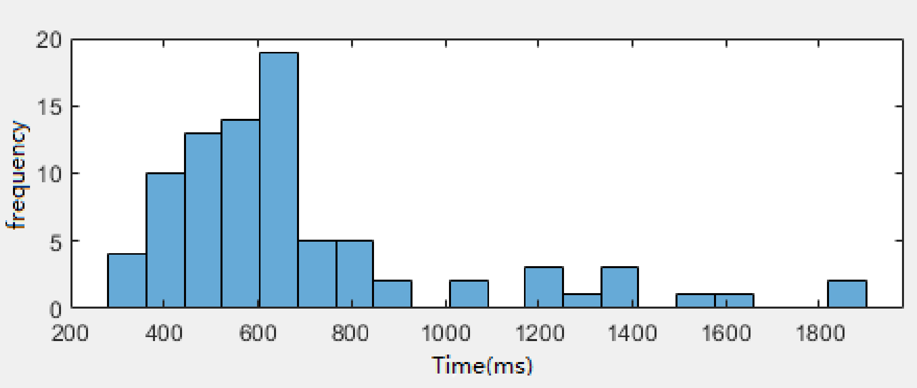

Figure 5 Histogram of JJ Interval in Time Domain Analysis

The system design combines lightweight and practicality, without introducing complex filtering or outlier removal modules. Instead, cross validation of data quality is achieved through graphical comparison of interval sequences. The test data was statistically analyzed, and the histogram of the JJ interval was obtained, as shown in Figure 5.

According to the histogram, it can be seen that the SDNN value matches the distribution width of the histogram. This test result can indicate that the test data has good stability.

5. Conclusions

The paper constructs a heart rate detection system based on BCG signals. And the HRV algorithm was used to solve the cardiac shock signal. A quantitative evaluation of the heart rate inversion algorithm was completed by analyzing parameters such as SDNN, RMSSD, and pNN50 in the time domain. The experimental test results have verified the feasibility and stability of this system.

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References

[1] Li Y H, Chen Y, Liu Y L, et al. Respiration and Heartbeat Signal Acquisition Method Based on Fiber Optic Sensing[J]. Chinese Journal of Lasers, 2022,49(04):95-106.

[2] Cátia.Tavares, Cátia. Leito, Presti D L ,et al. Respiratory and heart rate monitoring using an FBG 3D-printed wearable system[J].Biomedical optics express, 2022, 13(4):2299-2311.

[3] Atalay O. Textile-based, interdigital, capacitive, soft-strain sensor for wearable applications [J]. Materials, 2018, 11(5): 768-775.

[4] Karacocuk G, Höflinger F, Zhang R, et al. Inertial sensor-based respiration analysis[J]. IEEE Transactions on Instrumentation and Measurement, 2019, 68(11): 4268-4275.

[5] De Fazio R, Greco M R, De Vittorio M, et al. A Differential Inertial Wearable Device for Breathing Parameter Detection: Hardware and Firmware Development, Experimental Characterization[J]. Sensors, 2022, 22(24): 9953.

[6] Zhong X, Xia T, Mei Q. An effective centre frequency selection scheme based on variational mode extraction and its application to gear fault diagnosis[J]. Insight-Non-Destructive Testing and Condition Monitoring, 2022, 64(3): 155-163.

[7] Di Tocco J, Raiano L, Sabbadini R, et al. A Wearable System with Embedded Conductive Textiles and an IMU for Unobtrusive Cardio-Respiratory Monitoring. Sensors (Basel). 2021 , 21(9):3018.

[8] Lo Presti D, Bianchi D, Massaroni C, et al. A soft and skin-interfaced smart patch based on fiber optics for cardiorespiratory monitoring[J]. Biosensors, 2022, 12(6): 363-371.

[9] Zhichao Liu, Jinhua Yang, Juan Wang, et al. Design of modified model of intelligent assembly digital twins based on optical fiber sensor network[J]. Digital Communications and Networks, 2024, 10(5): 1542–1552.

[10] Issatayeva A, Beisenova A, Tosi D, et al. Fiber-optic based smart textiles for real-time monitoring of breathing rate[J]. Sensors, 2020, 20(12): 3408.

[11] Jiang X, Geng D Y, Zhang YY, et al. BCG signal de-noising method research based on EMD-ICA [J]. Chinese Journal of Biomedical Engineering,2019,38(02):138-145.

[12] Kong L Q, Wu Y H, Pang Z G et al. Measurement of Heart Rate based on Ballistocardiography [J]. Chinese Journal of Laser,2020,47(02):430-438.

[13] Zhao J, Chen X, Zhang X, et al. A solution for co-frequency and low SNR problems in heart rate estimation based on photoplethysmography signals[J]. Medical & Biological Engineering & Computing, 2022, 60(12): 3419-3433.

[14] Zhichao Liu , Taoping Shao , Xi Zhang. BCG signal analysis based on improved VMD algorithm[J]. Measurement, 2024, 231(114631): 1-10.

[15] Shao Taoping, Liu Zhichao, et al. Design of pulse and respiration monitoring system based on fiber optic sensing and VMD-FPR processing algorithm[J]. Optical Fiber Technology, 2022, 73(103033): 1-10.

[16] Zhichao Liu, Zhang Xin, et al. Heartbeat and respiration monitoring based on FBG sensor network[J]. Optical Fiber Technology, 2023, 81(103561): 1-10.