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Advancements in Multi-Sensor Wearable Devices for Cardiovascular Disease Monitoring and Treatment

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Abstract: Cardiovascular diseases are a leading cause of mortality globally, underscoring the urgent need for advanced monitoring and treatment solutions. Multi-sensor wearable devices, with flexible electronics and smart wearable devices, have great potential for continuous cardiovascular health monitoring and adjunctive therapy. This paper reviews the principles and functions of widely used sensor types, including piezoelectric, photosensitive, and thermal sensors. It introduces the key technological advancements, such as multi-sensor fusion and low-power designs, and their applications in disease monitoring and early intervention. Furthermore, the paper identifies current limitations, including accuracy, usability, and scalability, and provides insights into future directions for integrating wearable technology into cardiovascular disease management.

Keywords: Wearable devices, Cardiovascular disease, Multi-sensor fusion, Health Monitoring

1. Introduction

As society continues to evolve, the standard of living of the population continues to improve, the lifestyle, dietary habits, and health behaviors of the population have changed significantly, the population at risk of cardiovascular disease is large, the population is aging at an accelerated rate, cardiovascular morbidity and mortality continue to increase, and the tipping point for the reduction in the burden of disease has not yet been reached. It is estimated that more than 17 000 000 people worldwide suffer from cardiovascular disease, resulting in around 17.9 million deaths each year[1]. Cardiovascular disease surveillance and adjuvant technologies should be vigorously developed to foster the transition from disease to health and achieve disease prevention and health promotion.

Cardiovascular diseases (CVD), which include a wide range of conditions such as coronary heart disease, heart failure, and arrhythmia, are a leading cause of death worldwide. It also manifests itself in several ways, which can manifest as hypertension, dyslipidemia (low-density cholesterol, triglycerides, etc.), diabetes mellitus and chronic kidney disease (high albumin levels) and are generally manifested in changes in physiological parameters such as heartbeat regularity, high and low blood pressure, respiratory rate, cough and inability to lie supine (posture), which are associated with several human body systems such as circulatory, respiratory, locomotor and urinary, which are difficult to diagnose and treat[2].

Traditional diagnosis and monitoring of cardiovascular disease rely mainly on in-hospital devices such as electrocardiographs and ambulatory blood pressure monitors. Still, these devices have

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limitations, such as inconvenient use and limited monitoring time. In recent years, the development of wearable devices has provided the opportunity for long-term and continuous monitoring of cardiovascular disease. Multi-sensor wearable devices integrate different sensor technologies and can simultaneously monitor multiple cardiovascular physiological parameters, providing a new opportunity for early detection, condition monitoring, and assistive treatment of cardiovascular disease.

In the context of current technological advances in cardiovascular disease, the ECG is the most effective way of monitoring and assisting in the treatment of cardiovascular diseases. It works by recording the electrical signals the heart produces, caused by the exchange of ions between heart cells during each heartbeat. The heart's electrical activity is transmitted to the rest of the body and can be detected by electrodes placed in specific locations. ECGs are necessary when wearable devices are used for cardiovascular diseases[3].This article mainly focuses on the advantages and current applications of different types of wearable devices in the treatment of cardiovascular diseases.

2. Key Sensor Technologies in Multi-Sensor Wearable Devices

In line with the idea of developing systems engineering solutions triggered by the characteristics of cardiac physiological signals, according to the characteristics of different types of sensors to select the detection of different biological signals and then signal acquisition and processing before settling on a multi-sensor fusion and algorithms to solve the required signal output to assess the health of different people.

The aim is to convert biological signals, which occur in the clinical physiology of cardiovascular diseases, into electrical signals, machine-recognizable signals.

2.1. Piezoelectric sensors

These sensors are mainly based on the piezoelectric effect as the core, through a charge amplifier and a measurement circuit, amplifies these charges and converts the impedance, which is then converted into an electrical signal output proportional to the applied external force, i.e., it can be converted from mechanical energy to electrical energy. The piezoelectric effect is subdivided into a positive and a reverse piezoelectric effect, and in the case of multi-sensor wearable devices, it is usually a positive piezoelectric effect, i.e., in the form of an external force.

By combining piezoelectric sensor technology with peripheral arterial tonometry (PAT), cardiovascular health is assessed by measuring arterial volume pulse wave volumes at the fingertips. These sensors can facilitate early diagnosis and real-time monitoring of disease by continuously monitoring a variety of physiological indicators, such as the reactive vascular index (RHI)[4].

2.2. Photosensitive sensors

The principle of operation of photosensitive sensors is based mainly on the ability of photosensitive elements to convert light signals into electrical signals.

Using the photoelectric effect, when light is emitted from a PN junction, an electron-hole pair is formed, which forms a current proportional to the intensity of the light, e.g., the use of ultraviolet light sensors for DNA sequencing, infrared light sensors for body temperature measurement, PDT photo-labeling imaging, etc. The principle of photo-sensing is based on the principle of electron-hole pairing.

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2.3. Heat Sensors

The principle of operation of thermal sensors is mainly the use of materials at different temperatures to measure temperature in response to changes in resistance or capacitance, and these changes are converted into corresponding electrical signals that are exported. They are mainly divided into thermistor sensors, thermocouple sensors, and thermal capacitance sensors. Its current application is still mainly body temperature monitoring and auxiliary measurement of physiological parameters.

2.4. Heart rate sensors

PPG's photovolumetric pulse-wave-based method can be used for non-invasive detection of blood oxygen saturation in humans. The photovolumetric pulse-wave method is a non-invasive method for detecting changes in blood volume in living tissues by the reflection of red and infrared light. When a light beam of a certain wavelength is emitted from the skin surface of a fingertip, the light beam is transmitted or reflected to a photoelectric receiver, and the intensity of the light detected by the detector is attenuated by absorption by the skin muscles and blood at the end of the detection, with absorption of the light by the skin muscles, tissues, etc.[5]. The absorption of the light by the skin, tissues, etc., remains constant throughout the circulation and the volume of blood within the skin changes pulsatically under the action of the heart. When the peripheral blood volume of cardiac contraction is the greatest, the absorption of light is also the greatest, and the detected light intensity is the smallest; in diastole, just the opposite, the detected light intensity is the greatest, so that the light intensity received by the light receiver was a pulsatile change, the light intensity changing from a signal to a voltage signal, you get heart rate changes.

3. Multi-Sensor Fusion and Power Optimization Technologies

The main and most complex basic technology for wearable devices with multiple sensors is the combination of multiple sensors. It is capable of combining different sensors, working together to form a more complete and sophisticated system with more extensive functionality while effectively reducing the workload and power consumption of individual sensors in series and allowing the device to simultaneously use different sensor types such as radar, displacement, brightness, temperature and humidity, vibration, sound, etc. to achieve superior power consumption and transmission, and by combining data from different sensors, it improves the accuracy and reliability of monitoring.

3.1. Structure and principle of multi-sensor fusion

The basic principle of multi-sensor information fusion is similar to the comprehensive information processing process of the human brain; complementing and optimizing the combination of information from different sensors at multiple levels and in multiple spaces, it ultimately provides a consistent interpretation of the observed environment. This process requires the full exploitation of multiple data sources for rational use and manipulation, and the ultimate goal of information fusion is to derive more useful information through the combination of multi-level and multi-faceted information based on a separate observation table from each sensor. It not only exploits the cooperation of multiple sensors but also combines data from other information sources to improve the intelligence of the overall sensor system.

Multi-sensors, according to the level of information fusion of the sensor, can be roughly divided into three parts, with data fusion for the most basic part, this part is largely limited by the individual performance of the sensor and the functional level of the system. The second stage is the fusion of the feature map layer, although the data can be largely compressed, the data volume is too large, and the accuracy of the results is largely limited. This is the final decision layer fusion, which can meet

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the basic requirements of most devices with fast response speed, high processing intensity, and high fault tolerance.

At present, most of the multi-sensor fusion according to the physical model and parameter classification method points mainly apply the following two information fusion methods: [6]

Kalman filter (KF): The process of information processing using the Kalman filter is generally divided into two steps: prediction and correction. This is not only a simple algorithm but also a very useful system processing scheme. It is a mathematical iterative, recursive computational method that provides an efficient statistical optimal estimation of pooled data, suitable for environments where data processing space and speed are limited due to its small storage and computational requirements. KF is classified into two types, namely Distributed Kalman Filtering (DKF) and Extended Kalman Filtering (EKF). DKF makes data fusion fully decentralized, while EKF can effectively overcome the effects of errors and instability in data processing. The effects of errors and instability on the data fusion process. The recursive nature of the Kalman filter algorithm makes it suitable for real-time data processing, without the need to store a large amount of historical data, and only a small number of state variables need to be maintained to complete an efficient state estimation; through the introduction of methods such as forgetting factor, the computational volume can be reduced and the efficiency of the algorithm's execution can be improved while guaranteeing the estimation accuracy. In the optimised Kalman filter, the efficiency of target tracking is improved by adaptively adjusting the one-step covariance matrix of the prediction; it can be conveniently applied to different scales and types of problems, ranging from simple scalar systems to complex multi-dimensional systems, and can satisfy different needs by adjusting the model and parameters, which improves the flexibility and universality of the algorithm [7].

Artificial neural network method: by mimicking the structure and operation of the human brain, data from sensors is used as network inputs, and certain intelligent tasks are performed by training the network with corresponding machines or models to eliminate interference from non-target parameters. The neural network method is efficient in eliminating cross-interactions of different factors in multi-sensor cooperation; it is easy to program, and the output is stableThe structure of ANN is naturally suitable for parallel computing, which can be accelerated by hardware such as GPU to dramatically improve the computational efficiency. In large-scale data processing and real-time applications, the training and inference time is shortened by parallel computing; at the same time, optimisation algorithms , such as gradient descent method, momentum method and adaptive learning rate optimisation algorithms, improve the convergence speed of the network and training efficiency. By reasonably selecting and adjusting the optimisation algorithm, the training process of the model can be accelerated and the processing efficiency can be improved. The other is low-power model , which reduces the energy consumption of the model and improves the computational efficiency by introducing innovative structures such as spiking neurons and attention mechanism. For example, Spike Aggregation Transformer (SAFormer) combines the low-power characteristics of SNN and the high-performance advantages of Transformer to achieve high accuracy and low energy consumption on multiple datasets.

3.2. Low power-cost design

By using the latest ultra-light MCU (microcontroller unit) and optimizing power consumption in multiple dimensions, power consumption can be significantly reduced. This not only reduces the battery load and size but also allows one to make a very small front-end device with an exceptionally long runtime, making the design of low-power modules one of the biggest limiting factors in realizing the versatility of multi-sensor functionality. The current heterogeneous architecture based on Zynq Soc is expected to be a low-power portable multi-sensor system.[8]

4. Practical Applications of Multi-Sensor Wearable Devices

4.1. Application of the radiant heat principle

This type of multi-sensor wearable device collects information mainly through thermal sensors, with the black body radiation principle being the main basic design, and the radiation obtained by calculation can be derived from both body temperature and the thermal radiation of each organ. Similarly, the system also uses light-sensitive sensors to monitor changes in the light transmittance of human arteries, which can also detect pulse waves, but this method is affected by the respiratory rate, resulting in unstable pulse waves that still require further post-processing.

This system can be applied to monitor the subject's heart rate under conditions to ensure normal vital functions of the subject, which can be effective in cardiovascular diseases such as heart failure, respiratory sinus arrhythmias, etc., and at the same time, it can provide early warning of some unexpected cardiovascular and respiratory diseases[9].

4.2. Traditional model

In this developed system, two sensors are generally used: an acoustic sensor and a photosensitive sensor. Among them, an acoustic sensor can be placed on the surface of the chest cavity, and the heartbeat is calculated by recording the chest muscle contraction and diastole when the heart is beating; two sets of optical sensors are placed on the wrist to obtain the heartbeat pattern[10].

This system is simpler to design, can only achieve simple goals, and generates more noise and artefacts when collecting data via patch sensors, but it has better performance in terms of the feeding function.

4.3. Combination of ECG and EMG

Another new technology that has emerged based on the current technology is a further development of the traditional multi-sensor wearable devices. This means that overcoming the shortcomings of traditional ECG measurements at predetermined points and regular intervals can be applied not only in clinical practice but also to consumers for cardiovascular disease monitoring and prevention[11].

Under the new proposed algorithm, multiple EMG sensors will be placed at different locations on the body to collect muscle tension signals and make estimates and comparisons, eliminate noise and artifact interference to infer the location of the R-peak, and assuming R-peak fixation, use matching software to combine multiple consecutive R-peaks to obtain an image and calculate the instantaneous heart rate. Noise is filtered out after setting a threshold for the system data using a fixed algorithm. The results can also be compared to show that measurements from such systems are characterized by high accuracy.

This type of algorithm can be used to obtain accurate ECG signals in real-time and in situ using a combination of EMG and ECG when the consumer is still in a physiological state of normal exercise, which can be used as reliable information for cardiovascular disease monitoring and early warning purposes.

5. Discussion

While multi-sensor wearable devices have demonstrated immense potential in cardiovascular disease management, several challenges remain. For instance, balancing convenience, accuracy, and versatility poses significant design constraints. Although most multi-sensor wearable devices can achieve several basic functions, people with different needs have to choose devices with different performances, for example, in the treatment of patients with cardiovascular diseases, a device should be chosen to give preference to higher accuracy, in-home rehabilitation, real-time should be chosen, without affecting the vital signs of the device.

At present, these instruments can also be optimized by algorithms and model modification, applied to airline pilots, firefighters, medical personnel, and other special groups, and can be their special working environment promptly through the monitoring of ECG signals to respond to life safety or issue timely warnings[12].

6. Conclusion

The integration of wearable devices and medical systems represents a transformative advancement in cardiovascular disease management. Researchers and consumers favor more wearable devices with multiple sensors, as they allow for greater functionality, better reduction of energy consumption, and, at the same time, ensure data accuracy. By enabling continuous monitoring, personalized care, and early intervention, these devices hold the potential to improve patient outcomes and reduce healthcare costs. Future research should focus on developing a standardized data exchange platform, optimizing power efficiency, and integrating AI for predictive analytics. By addressing these areas, wearable technology can advance from a supporting tool to a cornerstone of modern healthcare, offering improved accessibility, accuracy, and functionality.

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