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Wearable Devices in Healthcare: Technological Advancements, Clinical Applications, and Future Horizons

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Abstract: This article provides a comprehensive review of the development of wearable devices in the field of healthcare. Key technologies such as sensor technology (e.g. electrochemistry, optics, etc.), micro-electro-mechanical systems (MEMS), flexible electronics, and material innovation are described in detail, power and energy management strategies, signal processing and data analysis methods are discussed. The clinical applications of wearable devices in diabetes management, cardiovascular disease monitoring and sleep monitoring are discussed, and their effectiveness and challenges are assessed. In addition, existing technical, clinical, and market challenges are analyzed, and future trends such as multimodal sensor fusion, intelligence, miniaturization, and integration with emerging technologies are predicted. Overall, this paper presents the current status of wearable devices in the field of healthcare in an all-round way, and provides ideas for subsequent research and development.

Keywords: wearable devices, healthcare, sensor technology, MEMS, flexible electronics, energy management, clinical applications, future trends

1. Introduction

In recent years, the healthcare sector has evolved with the help of wearable devices in the recent past. These devices that are to be worn on the body have come forward as an important device for the purpose of continuous and non-invasive monitoring of various physiological and biochemical parameters. They include electrophysiological, kinematic, thermoregulatory, and biochemical sensors, to name but a few. For example, wearable electrophysiological sensors can record and detect the electrical signals from the heart (ECG) or the brain (EEG) and thus help in identifying the risks associated with cardiac and neurological problems. Thus, kinematic sensors are useful in following the movements of the body and can be used in performance enhancement in sports as well as in the treatment and therapy of various diseases. Thermoregulatory sensors are useful in measuring temperature of the body, which can be a sign of a disease such as fever or hypothermia [1]. Biochemical sensors are able to detect and analyse biomarkers in sweat, tears and interstitial fluid and thus represent new possibilities for non-invasive health monitoring [2-17].

Harnessing Technology for Proactive Health Management The growing demand for preventive healthcare has given rise to the development of wearable devices that aid in the monitoring of health metrics and enable early detection of potential health conditions. The rising incidence of chronic diseases and the focus on preventive health care have been driving the demand for technologies that can deliver real-time and continuous health care information. Wearable technologies allow patients

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to move from traditional episodic assessments that occur once every few weeks to a continuous monitoring of their health while providing a means for individuals to manage their own health. As an illustration, take diabetes management, where continuous glucose monitoring such (CGM) systems have completely transformed the way patients check their blood glucose levels. These types of systems, developed by companies like Dexcom and Abbott, have the capability to continuously monitor glucose levels in the interstitial fluid and transmit the data to the receiver or a smartphone in real-time, permitting the patient to make timely changes to their diet/exercise/medication regimens [18-26].

The goal of this paper is to address the need for a comprehensive and in-depth overview of wearable devices in healthcare. This provides multiple novel insights and contributions. Firstly, it provides a comprehensive and current overview of the various technologies and materials used in wearable devices, discussing recent developments in sensor technology, microfabrication techniques, and flexible electronics. Secondly, it systematically investigates the wide range extent of clinical applications of wearable devices in various fields of medicine, including but not limited to diabetes management, cardiovascular monitoring and sleep medicine. Third, it critically characterizes the challenges of wearables, such as technical limitations, clinical validation and user acceptance. Lastly, it presents a forward-looking view on future trends and potential advancements in the field, touching upon areas such as multi-modal sensor fusion, energy harvesting and management, and integration with emerging technologies like artificial intelligence and the Internet of Things (IoT).

The rest of the paper is structured as follows. Wearable devices are the perfect intersection between the digital and physical worlds because they have several key technical characteristics (such as light weight, portability, mobility, and data processing capabilities) that can fill the gap between different types of data sensors (such as environmental, physical, behavioral, chemical, and psychological sensors), enable real-time digital communication, and enable instant decision making. We will briefly explore the architecture of wearable devices, covering sensor technology, micro-electro-mechanical systems (MEMS), flexible electronics, and power and energy. Subsequently, the clinical application cases and effect evaluation of wearable devices will be detailed, and the specific circumstances of their success in different medical scenarios will be analyzed in depth, as well as the challenges faced in the clinical application process. We will then focus on the technical, clinical and market challenges facing wearables and explore future trends and potential solutions. Finally, this article will summarize key research findings and discuss the future development of wearable devices in the field of healthcare. In addition, in order to further expand the depth and breadth of the research, we also carried out innovative exploration from the perspectives of interdisciplinary integration, comparative research and new functional assumptions. In the aspect of interdisciplinary integration, combined with the research results of new nanomaterials in materials science, the optimization effect of the new nanomaterials on the performance of wearable devices is discussed. Introduce artificial intelligence algorithms from computer science to more accurately analyze physiological data collected by wearable devices. From the perspective of comparative study, the continuous glucose monitoring (CGM) systems of different brands were compared in depth, and evaluated from the aspects of detection accuracy, user experience, and data transmission stability, so as to provide a more comprehensive reference for clinical application and patient selection. At the same time, based on the existing technology and clinical needs, a new idea of integrating a variety of sensors is proposed for wearable devices, which can not only monitor physiological parameters, but also detect the impact of harmful substances in the environment on human health in real time, providing people with more comprehensive health protection.

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2. Technological elements and functional realization mechanism

It is crucial to understand the essence of wearable devices and the mechanism of functional realization so that wearable devices can be developed. The device is co-formed by sensor technology, MEMS, flexible electronics and material innovations. Electrochemical sensors are good for metabolite detection such as glucose monitoring [18-21]. Optical sensors for heart rate struggle with motion artifact [27-39]. MEMS allows for the miniaturization and integration of accelerometers and gyroscopes [40-45]. Flexible electronics often employ materials such as polyimide and PDMS for comfortable monitoring [1, 46-56]. New materials such as graphene boost the performance of sensors. Lithium-ion batteries and supercapacitors demonstrate traits needed for power and energy management. Energy harvesting devices including solar, thermoelectric, piezoelectric, triboelectric and biofuel cells are being created [54-55, 57-62]. Energy management techniques such as dynamic power scaling and sleep mode boost physical endurance. Wearables rely heavily on signal processing and data analysis. Physiological signals are noisy and have interference. Signal processing methods and data analysis techniques, such as machine learning and deep learning are also used to extract valuable information [1, 27-28]. Bluetooth, Wi-Fi, and NFC with security measures are used for transmitting data [1, 20].

2.1. Wearable devices' key technologies and materials

There are many key technologies and important materials in the development of wearable devices. Sensor technology lies at the heart of wearables. For instance, many electrochemical sensors have been used for the detection of the biomarkers. For example, in glucose monitoring studies, enzyme-based electrochemical sensors react specifically with physiological glucose in body fluid and generate an electric signal that is proportional to the glucose concentration. This principle was adopted by many continuous glucose monitoring systems [18-19]. Optical sensors are widely used in heart rate monitoring applications including photoplethysmography (PPG). Notable examples include pulse oximeters, which wear around its own finger, sending light through the skin and measuring the changes in the absorption of light through the skin to determine heart rate. But motion artifacts and other problems may compromise their accuracy while engaging in physical activities [27]. There is also ongoing research and development on biological sensors which are used to sense selected biomolecules or biological signals. However, some sensors can identify particular proteins or nucleic acids in the body fluid, which yields valuable information concerning disease detection.

Wearable devices have benefited immensely from Micro-Electro-Mechanical Systems (MEMS) technology. It allows for the miniaturisation and integration of sensors and actuators. MEMS technology allows to create microstructures on one small chip while fabricating accelerometers and gyroscopes in one manufacturing process. Take the accelerometer as an example; it can measure the human body's accelerations in three directions by means of the micro-electromechanical structure, which is of great significance for motion tracking and health monitoring. Such technology not only makes the device smaller and less power-hungry but also improves its performance and reliability [40, 41].

So far, flexible electronics technology has made the new kinds of wearable devices available and thriving. Polyimide and PDMS are examples of highly flexible materials that make devices bendable and stretchable. As flexible sensors must conform to the surface of the human body without interfering with the user's normal activities, these materials can also help ensure that the sensors can do so. To illustrate, there are flexible skin sensors that can be attached to the skin to continuously collect physiological signals such as electrophysiological signal and skin temperature [51, 52].

The continuous innovation of materials has promoted the development of wearable devices. Due to its good electrical conductivity and mechanical properties, graphene has been used in sensor

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electrodes to enhance the sensitivity and responsiveness of sensors. Nanomaterials are also used for the improvement of the sensors in terms of unique design and properties of nanostructures. Conductive polymers have good biocompatibility and can be used in the preparation of flexible electronic devices and sensors [1].

2.2. Wearable devices' functions and application fields

Wearable devices have a wide variety of functions and application fields in health care. Wearable electrocardiogram (ECG) monitors in physiological signal monitoring allow real-time recording of the heart's electrical activity, thereby assisting doctors in the diagnosis of several cardiac diseases. Wearable EEG monitors measure the electrical activities of the brain, and are prevalent tools for research and diagnostics of various neurological diseases. Also, body temperature, blood pressure, and respiration monitoring devices can constantly detect the human body's physiological condition. For instance, certain smartwatches come with sensors for heart rate and blood pressure monitoring, allowing them to catch abnormal changes on time and remind the user to take measures [1, 35].

Wearable devices also play a significant role in sports and health management. It can precisely track users' movements data, such as steps walked, distance traveled while running, and calorie burned. This data is analyzed in order to give users custom exercise schedules. Thus, wearable devices also can filter the sleep status of users, such as sleep stages, sleep duration and sleep quality. The analysis of sleep data will provide users with their sleep suggestions to stay in good sleep health [63-67].

Wearable devices have shown a lot of promise in disease diagnosis and management. For example, in diabetes treatment, continuous glucose monitoring systems can continuously monitor the patient's blood glucose level, providing real-time data for patients to adjust their diet, exercise and insulin dosage. For example, in the management of cardiovascular diseases, doctors can predict the risk of diseases and evaluate the treatment effect through wearing devices that monitor patients' heart rate variability and blood pressure changes. The Zio Patch is a wearable ECG monitor that records a patient's ECG for extended periods of time; such devices are advantageous in diagnosing and treating arrhythmia and other diseases [66].

New functions of wearable devices have been brought to wearables by microfluidic technology. In sample collection, microfluidic channels can collect a variety of body fluids like sweat, interstitial fluid in minimally invasive manner. In some studies, detection of multiple biomarkers has been shown in body fluids using microfluidic sensors; for instance, sweat gluco, lactate, and electrolytes can be comed simultaneously. Additionally, microfluidic technology can be utilized for signal transduction and amplification. Such as, the weak signals from the sensor can be amplified and transferred stably through microfluidic structures. Microfluidic sensors are filled with working fluids and can detect mechanical stress and strain in mechanical sensing. In energy supply, microfluidic technology can be integrated with energy storage systems such as micro-supercapacitors or flexible batteries to provide power for wearable devices. [65-76].

2.3. Wearable devices' power supply and energy management

The power supply, energy management of wearable devices is one of the key aspects that affect their performance and application.

Wearable devices are typically powered by lithium-ion batteries and supercapacitors. Lithium-ion batteries have a decent energy capacity and can hold a relatively large amount of energy for its size, thus they are used in most of the many wearable devices. Yet they also come with a downside, which includes limited battery life and quite a lengthy charge time. Supercapacitors can be charged and discharged quickly, but are relatively low in energy density. In certain applications, such as those that

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require high power outputs in a short amount of time or frequently charge and discharge, supercapacitors have distinct advantages [54, 55].

The harvesting technology of the energy has turned into the research hotspot of the wearable device field. Photovoltaic cells: Solar energy harvesting technology uses photovoltaic cells to convert sunlight into electrical energy. Some outdoor-use wearables can incorporate solar panels to collect solar energy to power the device. Thermoelectric energy harvesting technology can transform the temperature gradient between the human body and the outside world into electrical energy. Piezoelectric energy harvesting and triboelectric energy harvesting could possibly produce energy from the mechanical stress or the friction of the human body against another material during movements. As in footwear or clothes, for example, piezoelectric materials can be installed to capture the energy that is produced when walking. For example, biofuel cells can wear out the metabolic substances that are in the body fluid and use them to generate electricity, such as lactate in sweat. Biofuel cells have been employed to supply power in some sweat-monitoring wearables [52, 57-60].

Energy policy plays a key role in wearable devices as well. Dynamic power adjustment adjust the power consumption of the device according to the actual working state. For instance, the power consumption can be reasonably reduced, such as reducing the sampling frequency of the sensor or turning off some functions that are not needed in particular scenarios, when the device is in a standby state or the monitored physiological signal is relatively stable. Sleep mode is a good way of saving energy. When not used for a period of time, the device is in the sleep mode to reduce power consumption. Silicon low-power design of electronic components and circuits can also greatly reduce the power consumption of the device as a whole. These energy management techniques can significantly increase the energy efficiency and longevity of wearable devices [50].

2.4. Wearable devices' signal processing and data analysis

Wearable devices generate and capture signals, and data in an elaborate manner and need applicable signal processing as well as data analysis methodologies to accumulate meaningful information.

Wearable devices are capable of collecting a wealth of physiological signals and miscellaneous data; however, these pieces of information are often highly distorted with noise, interference or nonlinear components. As an example, the muscle artifacts and the electrical noise in the surrounding environment can distort electrocardiogram (ECG) signals. Human activity creates common motion artifacts in signals such as those collected from accelerometers and optical sensors. These issues can greatly influence the quality and trustworthiness of the data. These challenges can be solved by using advanced signal processing techniques. The purpose of filtering techniques is using low-pass, high-pass, and band-pass filters to remove unwanted frequency components. This requires amplification to strengthen weak signals so they can be detected and analyzed. Steps include wavelet denoising and adaptive filtering for noise reduction and improving signal-to-noise ratio. To enable further processing and analysis, feature extraction methods are utilized to extract and characterize the signals in order to obtain the most relevant features. In ECG signal processing, for instance, QRS complex extraction is essential for the diagnosis of cardiac arrhythmias [1, 27-28].

Data analysis methods are indispensable for wearable device applications. Taking advantage of statistical analysis to find basic parameters as mean, standard deviation, and correlation of data for a general description of the physiological state Some of the machine-learning algorithms used include decision trees, integration vector machines, and neural networks. For disease classification, a neural network can be trained to classify normal and abnormal ECG patterns, useful in the diagnosis of cardiac diseases. Deep learning methods, particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have demonstrated excellent performance when dealing with complex physiological signals and time series data. Through that process, they can learn the data features by itself and predict accurately. RNNs can be used for analyzing sleep data to model sequential patterns of sleep stages to evaluate quality of sleep.

Calibrating the sensor response versus concentration of multiple analytes can occur with multivariate methods. Using the biomarker profiles, the pattern recognition algorithms can classify different physiological states. These techniques can further help in identifying abnormal conditions with respect to glucose and lactate levels in the analysis of sweat [68-70, 77-83].

Wearable devices mainly adopt wireless communication technologies, including Bluetooth, Wi-Fi, and NFC to create a data transmission environment. Bluetooth is extensively used for short-range data communication between the device and a phone or other nearby devices. It supports relatively low power consumption and easy pairing. Note: Wi-Fi is faster with a higher data transfer rate; therefore, it is much better to use a Wi-Fi connection for transferring a large number of data once the device is connected to a Wi-Fi connection. NFC is short range, so it is used for quick-pair and small data transmission. The data are encrypted to ensure they are safe when transmitted. This is done through strong encryption algorithms such as AES (Advanced Encryption Standard) to prevent data from being intercepted and understood by unauthorized parties. Authentication features, including password authentication or biometric identification, are employed to verify that users access device information. Also, privacy protection regulations and standards are complied with to protect personal health information of the users [27].

3. Clinical practice and future perspectives of wearable devices

The use of wearable devices is becoming more prevalent in clinical practice. Continuous glucose monitoring (CGM) systems, such as Dexcom's G6 and G8, can lead to better glycemic control in diabetes management (Week 6 Report). Cardiovascular disease monitoring devices such as iRhythm's Zio Patch for diagnosis and post-operative monitoring [22-24]. Devices used to monitor sleep help in diagnosing SAHS [7]. Other methods have potential as well [68-83]. However, hurdles still remain with respect to patient acceptance, data interpretation, and clinical validation.

Wearable devices still have technical hurdles to overcome, specifically in the areas of sensor performance and energy, as well as clinical and market obstacles. However, some favorable trends like multimodal sensor fusion, intelligence, miniaturization, and integration with emerging technologies exist. Microfluidic technology is also considered promising for better integration and multi-parameter monitoring [1, 77, 78].

3.1. Wearable devices' clinical application cases and effect evaluation

The utility of wearable devices has been explored in a number of clinical settings and assessed through different approaches.

CGM systems have shown clinically meaningful value in diabetes management. Devices such as Dexcom's G6 and G7 models can continuously measure glucose in the interstitial fluid. Through a receiver or smartphone application, patients are able to directly visualize their blood glucose trends over time. This enables timely adjustments in insulin dosing, diet and physical activity. Studies have demonstrated that the implementation of CGM systems in clinical practice significantly reduces both episodes of hypoglycemia and hyperglycemia in patients, resulting in improved glycemic control. Which showed for instance that in a long-term follow-up study of diabetic patients using CGM the decrease the average HbA1c with a of certain percentage when compared with the use of conventional self-monitoring of blood glucose methods [18].

Wearable ECG monitors have been playing pivotal roles in cardiovascular disease monitoring. The iRhythm Zio Patch records the electrocardiogram for weeks at a time. It has also identified thousands of cases of arrhythmia that traditional short-term ECG recordings never picked up. The

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Zio Patch, a wearable ECG monitoring system, can be associated with a high number of abnormal ECG events, making it a valuable tool in the diagnostic process for patients with suspected arrhythmia. It has also been applied in the follow-up of patients following cardiac surgery to evaluate cardiac recovery and identify complications early [27-29, 84, 85].

Wearable devices with sensors that detect sleep stages, heart rate, and respiration are used for sleep monitoring. These devices can detect the alterations in breath during sleep, and therefore can be used for the diagnosis of sleep apnea-hypopnea syndrome (SAHS). Based on data, it can determine how often and how sustained are the apnea events. The high prevalence of abnormal breathing events detected in a sleep study with the wearable sleep monitor had driven further diagnosis and treatment of SAHS in patients with suspected SAHS. This has improved the quality of life of patients by allowing the early intervention for sleep disorders.

There is also evidence of the potential of microfluidic-based wearable devices for clinical applications. Analysis of sweat biomarkersDevices can monitor changes in the levels of some of the components of sweat during exercise or in some disease states. For instance, the wearable microfluidic device could track sweat sodium and potassium levels during exercise in athletes and inform hydration status and electrolyte balance in real time. Microfluidic sensors are used to diagnose this disease by detecting the high levels of chloride present in the sweat of cystic fibrosis patients. Association between blood analytes and sweat biomarker levels has been examined in previous studies. A few studies found a reasonably positive correlation, indicating promising opportunities for sweat analysis in non-invasive disease surveillance and diagnosis. But more studies needed to establish more accurate and reliable relationship [76-83, 86].

To rigorously investigate how well wearable devices perform in a clinical context, a suite of assessment methods have been deployed. The performances are measured by comparing device readings with gold standard laboratory tests or actual clinical diagnosis. Assuming a continuous glucose monitor (CGM) is operating normally, the accuracy of the CGM system is reported based on a comparison of CGM-measured glucose values with values obtained from venous blood samples. We will test reliability by using the method of multiple-measurements and long-term stability tests. We determine sensitivity and specificity to evaluate the ability of the device to correctly identify positive and negative cases. In applications for disease diagnosis, a high sensitivity guarantees that the device can detect the disease in a timely manner, and a high specificity reduces the false positive rate. These devices must undergo clinical trials and observational studies under highly regulated protocols in order to confirm their effectiveness and safety. Such studies include numerous patients and extended follow-up, allowing for a complete assessment of the devices in the practical clinical milieu [18-20].

Although there are promising applications of wearable devices on the clinical field, challenges still exist. Patient acceptance is also an important consideration. The devices may be uncomfortable to wear, or difficult to navigate for some patients, and compliance may be affected. Interpretation of data can also be tricky given a lot of data coming from different sensors. They need to train clinicians to be able to analyze and use the data. There is still a lack of harmonization in validation standards, as much will be determined by clinical relevance and have yet to be more deeply reported in the aggregate to provide comparability between devices. In response, researchers are optimizing the devices for comfort and usability, creating software for easier data analysis, and developing more standardized clinical validation processes [27, 30-31].

3.2. Innovative exploration of wearable devices in the field of healthcare

In healthcare, wearables are playing an increasingly important role. With the continuous progress of science and technology, new functional ideas are proposed from the perspective of interdisciplinary

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integration and comparative research, which can inject new vitality into the development of wearable devices and bring more innovative results to the research in this field.

The development of wearable devices cannot be separated from the cross-integration of multiple disciplines. Advances in materials science offer new possibilities for optimizing sensor performance in wearable devices. In recent years, new nanomaterials such as graphene and carbon nanotubes have shown great potential in the field of sensors due to their unique physical and chemical properties. Graphene, for example, has excellent electrical conductivity, high specific surface area and good biocompatibility. The application of graphene to sensor electrodes in wearable devices can significantly improve the sensitivity and response speed of the sensor. When detecting biomarkers, graphene-modified sensors can more accurately capture low concentrations of target molecules, providing strong support for early diagnosis of diseases.

Artificial intelligence algorithms in computer science, especially deep learning algorithms, have revolutionized the analysis of massive amounts of physiological data collected by wearable devices. Taking sleep monitoring as an example, traditional sleep monitoring methods mainly rely on simple motion sensors and heart rate monitoring, which can only provide basic sleep duration and sleep stage information. By using deep learning algorithms, such as convolutional neural networks (CNN) and recurrent neural networks (RNN), multi-modal sleep data can be comprehensively analyzed, including heart rate variability, body movement, EEG and other information. By learning from large amounts of sleep data, the model is able to more accurately identify different sleep stages and even predict abnormalities such as apnea that may occur during sleep. Based on these analysis results, users can be provided with personalized sleep improvement programs, such as adjusting the rest time according to sleep quality, recommending appropriate exercise and diet plans, etc., so as to realize the transition from simple sleep monitoring to active sleep health management [87,88].

In this important medical scenario of diabetes management, continuous glucose monitoring (CGM) systems play a key role. There are several brands of CGM systems on the market, such as Dexcom's G6 and G8, and Abbott's FreeStyle Libre. An in-depth comparative study of these different brands of CGM systems will help clinicians and patients have a more comprehensive understanding of the characteristics of each product, so as to make a more appropriate choice.

In terms of detection accuracy, different brands of CGM systems use slightly different technical principles, which leads to differences in their detection accuracy. Dexcom's G series products usually use enzyme-based electrochemical sensors to determine blood glucose concentration by detecting the electrical signals generated by the reaction of glucose and enzymes in interstitial fluid. Abbott's FreeStyle Libre uses inductive glucose monitoring based on biosensor technology. Studies have shown that the accuracy performance of CGM systems varies among brands at different blood glucose levels. During the period of rapid changes in blood sugar, the test results of some products may have a certain lag; When blood sugar is relatively stable, the accuracy difference between brands is relatively small.

User experience is also an important factor affecting the application effect of CGM system. The comfort of wearing, the ease of operation and the intuitiveness of data display will affect the patient's use compliance. For example, the wearing of sensors in some products is more complex and may cause inconvenience to patients; Others reduce discomfort by optimizing the sensor design to better fit the skin. In addition, the interface design of the data display is also crucial, and the concise and easy to understand data display can help patients better grasp the changes in blood sugar [89-90].

Data transmission stability is also critical for CGM systems. In practical use, stable data transmission can ensure that patients and healthcare professionals have timely access to blood glucose information so that appropriate treatment decisions can be made. Some CGM systems use Bluetooth technology for data transmission, which may cause data loss or transmission interruption when the signal interference is strong. Some new products try to use more advanced wireless communication

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technologies, such as low power wide area network (LPWAN) technology, to improve the stability and reliability of data transmission.

Based on existing technologies and clinical needs, wearable devices have great potential in terms of functional expansion. Imagine developing a wearable device that integrates a variety of sensors, which can not only monitor the physiological parameters of the human body in real time, such as heart rate, blood pressure, blood sugar, body temperature, etc., but also detect harmful substances in the environment in real time, providing people with more comprehensive health protection.

In the detection of environmental harmful substances, it can integrate gas sensors, ultraviolet sensors, etc. Gas sensors can detect harmful gases in the air, such as formaldehyde, benzene, carbon monoxide, etc. These gases are widely present in indoor decoration, industrial production and other environments, and long-term exposure may cause serious harm to human health. When the concentration of harmful gases is detected, the wearable device can issue an alarm in time to remind the user to take appropriate protective measures, such as opening the window for ventilation and wearing a mask. Uv sensors can monitor the intensity of UV rays in the environment and provide users with sunscreen recommendations based on different UV indices to avoid excessive exposure to UV rays that can lead to skin damage and skin cancer.

In addition, the wearable device can combine location technology and big data analytics to provide users with personalized health risk assessments. For example, when a user enters an area with severe air pollution, the device can assess the health risks the user may face in the environment based on the environmental data of the location, the individual's physiological condition and historical health data, and provide corresponding preventive measures and health recommendations. This kind of integrated wearable device with multiple functions will break the limitations of traditional wearable devices that only focus on physiological parameter monitoring, provide more comprehensive and more active services for people's health management, and show the broad development prospects of wearable devices in the future healthcare field.

4. Conclusion

Wearable devices are one of the greatest innovations in the healthcare domain and are important for rendering medical services, managing health, and preventing diseases. Wearable devices have evolved considerably over the last few years, owing to constant technology advancement in sensor technology, materials science, energy management, and data analysis. Wearable devices that go far beyond just tracking steps, heart rate, and calories burned are now able to track an extensive range of physiological and biochemical signals, and relay helpful information to patients and doctors for use in health management.

However, as we have mentioned throughout the paper, wearable devices still have many challenges. There are technical hurdles (in terms of sensor traits, power generation, signal processing, etc.) that must be addressed. These challenges need to be overcome to apply it clinically: regulatory compliance, integration with healthcare systems, user acceptance, among others. Attention is also needed to other market challenges, especially related to standardization and education.

In line with these challenges, the future of wearable devices in healthcare does seem hopeful. The trends development of wide range of Technological innovation, multi-modal integration, intelligence, miniaturization and application expansion provide the space of imagines. With the enhancement of cross-subject cooperation between engineering, medicine, materials science, and computer science, and continuous technological innovation, wearable devices are expected to play a more and more important role in the medical field. They can transform how we provide healthcare, leading to more personalized and preventive care, with positive implications for the health outcomes and quality of life of people. Cross-disciplinary collaboration between researchers, industry leaders, and

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policymakers will be essential towards overcoming these challenges, and enable achieving the full potential of wearable devices for healthcare.

Declaration of interests

The author has nothing to disclose.

Authorship

Siyuan Wang: Conceptualization, Investigation, Data collection, Data analysis, Writing, Review & editing, Visualization.

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