Research on Biosensor Technology in Wearable Health Monitoring Equipment

Jiaen Wang*

Institute of International Education, Xiamen University of Technology, Xiamen, China

*Corresponding author: yaohao@ldy.edu.rs

Abstract. In recent years, innovative and well-researched smart devices utilizing wearable biosensor systems for health monitoring have attracted much attention from society. These health monitoring devices, equipped with various transmission modules and miniature physiological sensors, are anticipated to alleviate the escalating healthcare expenses in the post-pandemic era by offering real-time, precise physiological information and persistent health status monitoring. Additionally, such health monitoring devices can provide tailored health advice and preventive measures for healthcare providers, potentially transforming the future of healthcare. Hence, their impact spans a broad and enduring spectrum in our daily lives. This paper aims to provide a comprehensive review of current technologies used for health monitoring and current trends, developments, and research in wearable biosensor systems for health monitoring. The focus is especially on the technical design of multiparameter physiological sensing systems and the challenges they face. Also, it discusses the ethical and data protection issues associated with these wearable biosensor systems. Finally, future research directions and perspectives on wearable biosensor devices are analyzed. Moreover, this paper serves as a resource for researchers and developers in this field, providing directions for future research advancements.

Keywords: Biosensor, health-monitoring, wearable devices.

1. Introduction

As is well known, in the post-pandemic era, various diseases are prevalent around the world, posing a serious threat to the health of the general public. During this period, prolonged social isolation and irregular lifestyles may lead to a surge in the number of illnesses in the population, and it is predicted that four noncommunicable diseases (cardiovascular diseases, chronic respiratory diseases, and diabetes mellitus) will cost the global economy $30 trillion from 2011 to 2030 [1], and in China the economic burden of diabetes mellitus per capita during the period from 2020 to 2030 will increase from 231 U.S. dollars to 414 U.S. dollars, with an annual growth rate of 6.02%, which indicates that the economic burden of diabetes in China is growing faster than the country's economic growth rate. [2] Also, mood disorders, irritability, insomnia, depression, and post-traumatic stress symptoms are likely to become more prevalent in the post-epidemic era after the quarantine period ends [3]. Healthcare data from 30 countries of the Organization for Economic Cooperation and Development (OECD) show that health spending around the world has increased over time [4], growing faster than the global economy. This makes it particularly important for the population to utilize wearable biosensor systems for disease monitoring and prevention and early detection and treatment of diseases by monitoring the body's physiological signals.

Wearable biosensor systems have garnered widespread attention. Their market demand has also escalated significantly [5], underlining the importance of innovation and research [6]. Simultaneously, the development of communication technology has significantly expanded the scope of physiological sensing systems. Moreover, they offer high-quality information services through mobile terminals, smart mobile terminals with multi-cloud storage [7], and other such devices. They enable full-time, uninterrupted health monitoring, thereby enhancing people's daily convenience. As a convenient, real-time, and continuous health monitoring tool, smart wearable devices have a wide range of application prospects in mass health management.

Typically, wearable systems for health monitoring consist of several miniature sensors that measure important physiological signals such as heart rate, blood pressure, blood glucose, and blood oxygen. These measurements are typically relayed wirelessly, through technologies such as Bluetooth or Wi-Fi, to a central node, analogous to a high-performance computer device such as a PDA, a microcontroller board, or a micro-server. This central node then processes and transmits the user's data or information to the appropriate device or panel. The concept is demonstrated in Fig 1.

Naturally, effective wearable devices for health monitoring must fulfill a variety of constraints and various criteria. These include real-time, accuracy, portability, durability, encrypted storage and transmission of the user's physiological data, and so on. Consequently, establishing such a system is intricate and challenging, as designers must navigate through multiple stringent and often contradictory demands to ensure precise and dependable measurement results. In the following paper, these wearable devices are scrutinized through four distinct perspectives: market, user needs and perceptions and acceptance, technical issues, ethical issues, and data protection, followed by concluding recommendations. Finally, a viewpoint on the future of this exciting area of research is presented.

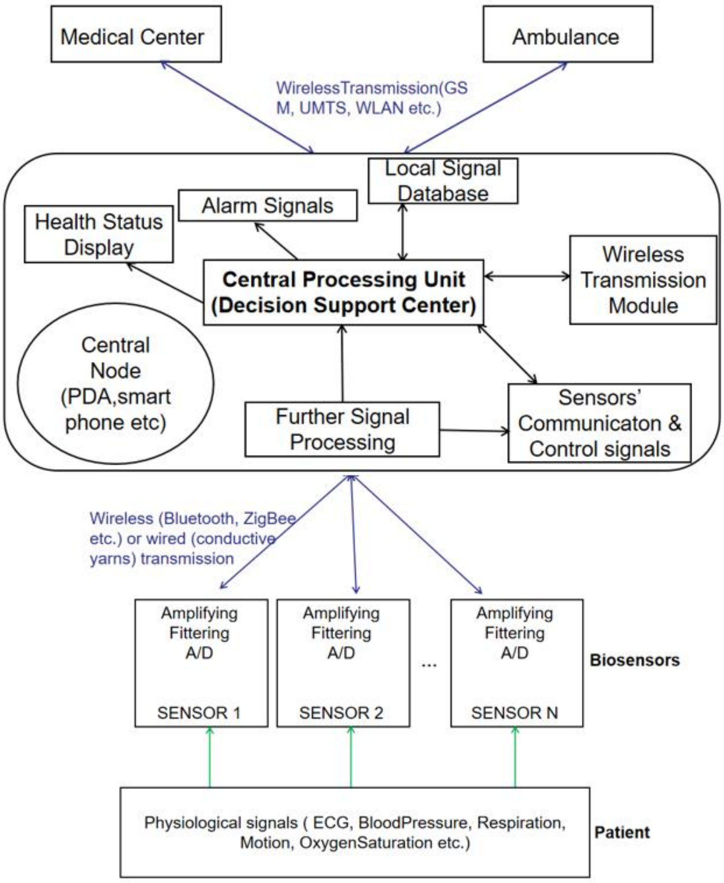

Fig. 1 A basic architecture of a wearable health-monitoring biosensor system.

2. Review

2.1. The Consumer Market of Wearable Devices

2.1.1 Development Trend and Market Size

Research on the development of wearable technology shows that it has three growth periods: the first stage is from the 1980s to 1997; the second period is from 1998-2000, and the third period is from 2001-2004 [8]. Subsequently, as advancements in science and technology garnered attention and consumers increasingly focused on health, wearable devices became an increasingly sought-after product in the consumer market. According to eMarketer, 29.5 million U.S. adults used wearable devices (including fitness trackers and smartwatches) in 2015, a significant increase of 57.7% over 2014's wearables market [9]. According to IDC's data, the worldwide shipment of wearable devices from 2017 to 2022 is projected to ascend from 135 million units to 492 million units, a compounded growth rate of 29.52%. Furthermore, it is projected that shipments will reach 27.9 billion units in 2023, reflecting an extraordinary growth trend.

As a result of technological innovation, increasing public health awareness, and increasing application of wearable devices in the medical and health management fields, the market size has been growing as well. The wearable device market continues to grow due to the launch of new products and features by Apple, Samsung, Xiaomi, and other technology companies to remain competitive and increase market share.

2.1.2 Primary Target Audience

Wearable devices send data to mobile or computer applications and the cloud to store and analyze the data via Bluetooth. Some of these devices have age-friendly designs that monitor health conditions and provide emergency help to help seniors better manage their health. Of course, fitness and sports enthusiasts are also a key audience. These users track their exercise data through the device, gaining real-time information to monitor their physical condition and adjust their health and exercise plans based on this information. Medical institutions also provide technical support by providing patients with wearable devices to conduct clinical testing and assist in drug judgment and medical decision-making [10].

2.2. User Requirements, Perception and Acceptance

For the general public, the design of wearable systems should address the following different layers of requirements: usability, functionality, durability, security and comfort, which generally serve as the basic criteria for user needs, perceptions, and acceptance [11]

2.2.1 Usability

From the perspective of user requirements, wearable devices for health monitoring should enable users to get started quickly without spending too much time and energy learning how to use the device. From the perspective of user perception, simple interface design and easy-to-use operation will have a direct impact on the user experience. Users expect devices to deliver an efficient and seamless experience, not disrupt or discomfort them. For instance, the device should respond promptly to user commands and offer clear visual or tactile feedback. By improving usability, we enhance user acceptance of wearable devices. Clear user guides assist first-time users with straightforward steps, reducing distress and enhancing acceptance.

2.2.2 Functionality

From the viewpoint of diverse user requirements, practicality and the value of a product greatly influence their buying decision. The device should be adaptable to cater to various user needs, including health monitoring, exercise tracking, and message notification. The enhancement of device functionality is directly proportional to user experience, according to user perceptions. When a device can provide useful functions that meet the actual needs of users, users will perceive the device more positively, which in turn affects their acceptance of the device. User acceptance, which is a significant factor in the success of a device in the fiercely competitive marketplace, is intrinsically linked to the level of functionality a device can offer. Consider a wearable health testing device that tracks a user's heart rate, steps, calories, and exercise time. Such a device, offering a multitude of useful features, would be more likely to be favored by users, thereby enhancing its marketability. Additionally, a device's adaptability and scalability play a pivotal role in user acceptance. Users expect devices to not only meet their basic needs, but also to be able to enhance their experience through software upgrades or the introduction of additional features to meet their other individual needs.

2.2.3 Durability

From the perspective of user needs, the general public tends to choose wearable devices with the hope that they can accompany them for a long time and are not easily damaged, to ensure the normal operation of the device. For instance, consider the case of wearable devices, such as smartwatches or fitness bands, which are innately designed to be worn on the body for extended periods, and so durability becomes a critical factor that users consider while making their purchase decisions. In the eyes of the user, the durability of the device chiefly influences the quality of the user experience. Frequent repairs or replacements will reduce their satisfaction with the device. Conversely, perceiving the device as durable enough to function reliably and stably would strengthen their trust in it. Ultimately, this user perception translates into significant success in the marketplace. Increased durability helps to extend the life of the device, reduces replacement costs for users, and improves user acceptance of the device.

2.2.4 Security

In the design of wearable devices, users are very sensitive to the security of their personal data and privacy, so wearable devices require strong security measures to ensure that user information is not threatened by unauthorized access and transmission. From the perspective of user needs, the general public expects their personal data, such as health metrics and exercise data, to be properly protected. Users expect devices to have advanced data encryption technology that can ensure that sensitive information is not cracked or stolen during transmission and storage. For user perception, the security of the device is directly related to the user's trust in the product, if the user feels that their personal information is easily threatened, reducing their motivation to use it. Finally, related to user acceptance, device manufacturers need to increase users' confidence in the security of their devices by adopting advanced security technologies, implementing sound authentication mechanisms, and ensuring that communications between the device and the cell phone or cloud service are encrypted and secure.

2.2.5 Comfort

Comfort is an important factor in the design of wearable devices that is directly related to whether users are willing to wear them for a long time. From the perspective of user needs, the general public seeks wearable devices that provide a comfortable experience. Lightweight design, ergonomic shape and structure, and choice of material are all important factors for users to consider when purchasing. From the perspective of user perception, the comfort of the device is directly related to the user's satisfaction with the product. If the device is not comfortable to wear, users may feel fatigue or discomfort in a short time, reducing their motivation to use it. Finally, related to user acceptance, improved comfort is critical to the success of the device in the marketplace. If a device provides a pleasant wearing experience, users are more likely to choose and accept the device. Therefore, improved comfort not only increases user satisfaction but also improves its competitiveness in the market.

2.3. Technical Issues

Wearable devices for health monitoring have made significant technological advances, but there are still some potential technical issues, and these flaws can affect device performance, user experience, and market acceptance, among other things. Here are some common technical issues in wearable devices:

2.3.1 Battery Life

Power consumption typically scales with device size, necessitating the design of today's power-hungry consumer electronics to accommodate significant battery space [12]. Nevertheless, this approach still possesses certain potential technical disadvantages. Currently, most wearable health monitors operate with computing capacity similar to cell phones. However, due to their small size, their battery capacity is typically only 11% of that of a cell phone. The short battery life severely hampers the use of applications that need to run for long periods of time [13]. Particularly in healthcare, implantable health monitoring sensors need to run for long periods of time without interruption to monitor the health of patients. This requirement necessitates batteries capable of enduring prolonged usage, which may not be feasible for patients due to limited ability to recharge or replace. Consequently, battery capacity limitations emerge as a key challenge for health monitoring devices. The limited size of the devices to accommodate large-capacity batteries is a direct result of the battery capacity limitation as a constraint affecting the performance of the devices. The compact size of the battery restricts its capacity to store energy, thereby significantly limiting the device's usage time after each charge.

Certain high-end wearable devices, designed for health monitoring, often incorporate power-hungry features such as high-resolution displays, multifunctional sensors, and frequent wireless communication. Such devices necessitate batteries. Moreover, unobtrusiveness and longevity in performance, particularly for implantable sensors, are imperative in healthcare [14]. While these attributes enrich the user experience, they also intensify the battery life issue. Insufficient battery capacity may result in the user needing to recharge the device within a short period, thus decreasing the device's lifespan. Users expect wearable devices to fulfill their 24/7 usage needs rather than frequent charging. However, limited battery capacity makes it difficult for devices to meet users' expectations for extended use, forcing users to potentially need to recharge multiple times during the workday, which contradicts users' desire for a simple and efficient use experience. For example, since the release of the Apple Watch Series 1 in 2015, the battery capacity of Apple's smartwatches has increased, and these batteries can be used for up to 18 hours of mixed-use, and when the battery is low, they switch to a power-saving mode, enabling consumers to read for up to three days straight [15]. Despite the slight improvement, the current battery life of smartwatches is still unable to meet the needs of consumers. This will not only affect users' daily usage habits but also negatively affect the competitiveness of the device in the market.

2.3.2 Precision and Accuracy

The health monitoring capabilities of wearable devices often rely on built-in sensors and measurement technologies, such as heart rate sensors, motion sensors, sleep monitors, etc. However, some wearable devices may have accuracy and precision issues with these sensors and measurement technologies.

In terms of motion monitoring, some wearable devices may have difficulty accurately differentiating between certain specific movements, which may bother users during actual activities and affect the accuracy of health monitoring data. Errors may exist for non-walking sports. For example, forms of exercise such as cycling, free-fighting, or strength training may be misclassified as walking, which affects the accurate monitoring of different exercise types. Changes in the user's posture, especially arm and wrist movements, may cause the device to incorrectly record additional steps. This can lead to deviations in step counts during activities such as typing and writing in daily life. It may also be difficult for complex and variable movements to be accurately recognized by the device. For example, it may be difficult for the device to distinguish the difference between slow walking, fast walking, and jogging, resulting in inaccurate step counts. Statistics may deviate from actual data. In one survey report, some devices reported 15% more steps than observed [16].

The physiological characteristics and physical differences of different individuals pose an important challenge to the accuracy of wearable devices. Everyone has differences in physical condition, physiological functions, and exercise habits, and some universally designed wearable devices may have difficulty adapting to this diversity, thus affecting the individual variability of monitoring results. For different body configurations, factors such as height, weight, and muscle mass vary, and these may have an impact on some measurements. Similarly, heart rate variations between individuals may be large and are influenced by a variety of factors such as age, health status, body fat percentage, etc., leading to differences in heart rate monitoring results for different individuals under the same activity. Taking wearable devices for sleep quality measurement as an example, it has been investigated that underestimation of the measured sleep onset latency (SOL) leads to errors in the results because of differences in accuracy between individuals, especially for individuals suffering from sleep disorders or other health conditions where there is too much variation and thus additional physiological signals carried by the activity recorder in the device [17].

Of course, the effects of the external environment may affect the performance of the sensor. For example, temperature, humidity, and other environmental factors may lead to inaccurate sensor readings. Increases or decreases in temperature may lead to changes in the sensitivity of the sensor element, which in turn affects its measurement accuracy. In high-temperature environments, sensors may produce data malfunctions due to overheating, while in low-temperature environments, certain sensors may become insensitive. For different lighting environments, such as direct sunlight or cloudy days, this may result in the readings of the optical sensors being affected. This may negatively affect the accuracy of the device when used outdoors. In an experiment on heart rate (HR) and energy expenditure (EE) measurements of three popular wrist-worn activity monitors at different exercise intensities, it was found that the limitation of this study was that it was conducted in a controlled environment (e.g., a laboratory), and therefore the results may not be generalizable to free-living activities and can only be used as a reference, and further HR may be needed due to the relative accuracy of HR field testing [18].

Some low-cost or low-quality wearable devices may use insufficiently accurate sensors, resulting in the accuracy of the measurements being compromised. Not only that, low-quality sensors may consume more power, resulting in a shorter battery life for the wearable device. In addition, these sensors may perform erratically over long periods of time or under specific usage conditions, compromising the reliability of the device. For example, aging heart rate sensors and motion sensors may not provide accurate heart rate measurements and have errors in tracking steps and activity intensity.

2.3.3 Software Stability

Software instability may result in a wearable device's application crashing or becoming unresponsive during operation. This can be troubling for users, especially if the device crashes while performing important functions, such as health monitoring, motion tracking, or notification alerts. Frequent crashes, lagging, or unresponsiveness can also significantly degrade a user's overall experience as users expect wearables to integrate seamlessly into their daily lives. Frequent software issues may affect the user's trust in the device. Users may begin to doubt the reliability of the device, reducing their trust in the device and questioning its performance. This can tarnish the user's perception of the brand.

2.4. Ethics and Data Production

Driven by advances in technology, the health monitoring capabilities of wearable technology are becoming increasingly integrated into people's daily lives. By collecting personal physiological, exercise and environmental data, these devices provide users with convenient functions and help them to provide comprehensive health alerts and monitoring services for themselves or their families. However, new ethical and data protection challenges have arisen, such as the fact that wearable devices used for health monitoring store an enormous amount of information that can be accessed by third parties, sometimes without the user's permission [19].

2.4.1 For Users and Producers

In today's widespread use of wearable devices, the huge volume of data generated by users is at the center of privacy concerns. This data, which includes sensitive health-related information, sleep patterns, exercise logs, and other personal attributes, significantly influences the user's concern for personal privacy. Users rightfully expect that this deep, personalized information will be properly protected, but in reality, we often witness a disregard for privacy policies and a low level of user concern for informed consent [19].

Despite the aim of wearable devices to decrease healthcare costs by monitoring and preventing disease or even predicting previously unforeseen events, users often do not pay enough attention to the details of privacy policies and informed consent. While using these devices, users may not be fully cognizant of how their data is collected, stored, and used, thereby adopting a passive stance on privacy protection. For instance, if a wearable device is constantly monitoring the user's health and transmitting data via Bluetooth, it inevitably collects a large amount of personal data. This might include physiological indicators such as heart rate and blood pressure, which are sensitive and personally identifiable data. While the device itself may store this information in a coded format, it can still be deciphered by a hacker, thereby jeopardizing the user's privacy.

The core challenge of the privacy issue lies in the game of rights and interests between different stakeholders. To provide more accurate health monitoring services, manufacturers of wearable devices have to collect and analyze data to a certain extent. This involves a certain degree of privacy intrusion, e.g., life-logging technology, implantable technology, etc. [19]. Therefore, there is a need to find a balance between the rights and interests of different stakeholders, including the privacy needs of the users and the incentives of the manufacturers to provide high-quality services, to ensure that the ethical implications are adequately considered and weighed.

2.4.2 For Third-party Attacks

Apart from the users themselves and wearable device manufacturers, third-party hackers also pose a considerable threat to user privacy. These unscrupulous hackers may pursue goals that are not limited to obtaining users' personal information but also include identity theft and impersonation, the use of user data for extortion, and other dangerous activities. Wearable devices used for health monitoring often act as a bridge for information transfer, as they upload users' data to the cloud for processing and storage. While such connectivity provides great convenience, it also provides hackers a potential avenue for intrusion. Upon successful breach of the cloud services linked to wearables, hackers may steal sensitive user data, including social accounts and biometric data. Consequently, this elevates the risk of identity theft and compromises an individual's privacy.

3. Improvements and Recommendations

3.1. Market

3.1.1 Customized Design for Key Target Audiences

Wearable device manufacturing companies should tailor their designs to meet diverse user needs, focusing on ease of use and health monitoring features for elderly and real-time information for fitness and sports enthusiasts. For healthcare organizations, partnering with tech companies to customize devices is important.

Ease of use is critical for elderly users, who may avoid new technologies if interfaces aren't intuitive and font sizes are large. Older people's focus on health makes health-monitoring features crucial. Integration of features like heart rate monitoring, step counting, and sleep quality analysis can provide real-time health data.

For fitness and sports enthusiasts, focus on real-time monitoring and data feedback. Given fitness activities' specific nature, device comfort and durability are key. Lightweight materials, waterproof design, and comfortable wearing style will affect the user's experience during exercise, thus increasing the user satisfaction and utilization rate of the device.

Collaborating with healthcare organizations is crucial for customized designs. Tech companies should customize devices that meet clinical testing and medical needs, such as ECG monitoring and blood glucose monitoring for diabetics. Such collaborations will foster the expansion of healthcare management and offer patients more precise health care.

3.1.2 Strengthening Cooperation within the Industry

Given the rapid growth of wearable technology, it is prudent for relevant companies to bolster intra-industry cooperation in a global technological surge. This will only expedite innovation, standardization, and data sharing, thereby creating a more conducive environment for wearable technology's long-term viability.

Companies within the industry can work together to address technical challenges and accelerate the launch of new technologies by sharing R&D resources, experience, and technical achievements. Joint development of new sensor technologies, energy-saving batteries, smart algorithms, and other innovations are expected to inject more vitality into wearable technology and increase its competitiveness in the market. Following this, the development of standards is crucial for the healthy development of the entire industry. Through intra-industry cooperation, companies can work together to develop technical standards, data formats, interoperability specifications, etc., to ensure that devices from different vendors can work together effectively. This not only enhances the user experience but also reduces production costs and enlarges the wearable technology market's scale. Lastly, data sharing among partners is another key factor driving innovation in the industry. By sharing anonymized user data, enterprises can better understand user behavior, needs, and preferences, providing a more accurate basis for product personalization and feature optimization. This collaborative data analysis is expected to provide companies with deeper market insights and drive the application of wearable technology in different fields.

3.2. User Requirements, Perception and Acceptance

For usability, wearable devices should be designed to provide clear user guides to ensure that users can easily get started, and adopt simple and intuitive interface design and easy-to-use operations to reduce user learning costs. The device should promptly respond to user commands and provide unambiguous visual or tactile feedback to enhance the user experience.

For functionality, device functions should be diversified to meet various user needs such as health monitoring, exercise tracking, and information notification. To enhance the utility of the device and ensure that the actual value of the function is proportional to the user's expectation. Emphasizing the adaptability and scalability of the device can enhance the user experience through software upgrades or the introduction of additional functions.

For durability, durable materials and designs can be used to ensure that the device is not easily damaged during long-term wear to emphasize the stability and reliability of the device, reduce the frequency of user replacement, and improve user satisfaction.

For security, encryption and security of communication between the device and the cloud service should be guaranteed to enhance users' confidence in the security of the device.

For comfort, lightweight, ergonomic shapes and structures should be designed to improve wearing comfort. Selecting comfortable materials can mitigate the fatigue associated with wearing the device.

For fashionability, attention should be paid to the appearance design of the device to make it more in line with the trend and personalized needs. Assuring diverse style options cater to the fashion preferences of varied users.

3.3. Technical Issues

Wearable device manufacturers have numerous strategies at their disposal to effectively address the battery-life issue. For wearable device tech companies, more emphasis can be placed on developing more energy-efficient hardware and software to reduce energy consumption and extend battery life. The development of smart energy consumption prediction, which utilizes machine learning and artificial intelligence algorithms to predict the future energy consumption of a device based on the user's usage patterns, time, and activities, and taking energy-saving measures in advance can also extend battery life. Secondly, the development of technologies that harness energy from the environment, such as motion charging or temperature difference power generation, should be considered. Such technologies help to recharge the battery to a certain extent and slow down the rate of decline in battery capacity. In addition, enhancing the charging speed so that users can access enough power in a short period can help alleviate concerns about the frequency of device charging and improve ease of use. The design of wearable devices' batteries as removable and replaceable simplifies the process of replacing aging batteries, thereby extending the overall lifespan of the device. Lastly, the introduction of an intelligent charging reminder system that dynamically manages the device according to the user's usage patterns and needs through the user's daily activities and device usage, improves battery utilization, and reminds the user promptly when to charge the device to avoid the unexpected situation of insufficient power.

When it comes to wearables, precision and accuracy are of paramount importance. The foremost consideration is the selection of superior, precise sensors, encompassing heart rate sensors, motion sensors, and other health monitoring sensors. The use of top-quality sensors ensures that the physiological and movement data of the user can be captured more accurately, thereby enhancing the precision of the monitoring outcomes. Secondly, intelligent algorithms for personalized adaptation have been introduced to enable the device to flexibly adapt to the physical characteristics and habits of different users. Such algorithms, equipped with learning and adjustment functions, continually adjust the monitoring model in response to individual changes, ensuring the provision of more precise data.

Several strategies have been developed to improve the software stability and performance of wearable devices. Initial strategies include regular software updates which resolve stability issues, introduce new features, and optimize performance, thereby continually enhancing user experience and aligning with market requirements. Next, a comprehensive user testing program simulates various usage scenarios, enabling the identification of potential issues at an early stage, thereby facilitating timely issue resolution, and facilitating understanding of the software challenges from the users' perspective, enabling adjustments and improvements. To collect user feedback more proactively, a bug reporting mechanism is introduced so that users can easily report problems, providing manufacturers with an immediate and direct source of information to respond quickly and improve the overall quality of the product. Lastly, the employment of cloud synchronization technology ensures prompt updates and upgrades of software and services, ensuring users always experience the most stable and latest software version, thus enhancing device maintainability and sustainability.

3.4. Ethics and Data Protection

Manufacturers should enhance user privacy education first, which includes explaining the collection, storage, and usage of collected data, and emphasizing the importance of privacy policies. Secondly, manufacturers need to implement strong encryption and security measures and promote industry standards to ensure devices have a high level of privacy and security. User control is also critical, and manufacturers should provide more control options and design concise and easy-to-understand privacy settings to make it easier for users to manage their personal information. In terms of multi-party collaboration, manufacturers, associations, government, and society should work together to develop sound privacy regulations and standards, and establish cross-industry cooperation mechanisms to defend against hacking. Manufacturers should promptly provide security updates and vulnerability remediation mechanisms, and users should be urged to update their devices and apps for the latest security and performance optimizations. Manufacturers should adopt anonymization techniques and data aggregation to protect user privacy. Personal identity should be separated from data, and services offered through information about overall trends and patterns rather than divulging data about specific individual users. Finally, by training users on cybersecurity and privacy protection, as well as providing alerts and educational features in devices or apps, security awareness can be enhanced. These measures together can help ensure that wearable devices provide convenience while maintaining user privacy and data security.

4. Conclusion

In conclusion, the rapid evolution of smart devices incorporating wearable biosensor systems for health monitoring has emerged as a transformative force in contemporary society. These devices, featuring advanced transmission modules and miniature physiological sensors, hold the potential to mitigate the surging healthcare costs post-pandemic by delivering real-time, precise physiological data and continuous health status monitoring. The ability of these health monitoring devices to offer personalized health advice and preventive measures not only empowers individuals but also has profound implications for healthcare providers, paving the way for a paradigm shift in healthcare delivery.

This comprehensive review has delved into the current technologies driving health monitoring, shedding light on the intricate technical design of multiparameter physiological sensing systems and the challenges they confront. The ethical and data protection considerations associated with wearable biosensor systems have been discussed, emphasizing the importance of user education, privacy protection measures, and collaborative efforts among stakeholders to strike a balance between convenience and data security.

Looking ahead, the future of wearable biosensor devices holds promising prospects. The analysis of current trends, developments, and ongoing research underscores the potential for continued innovation and refinement. The identified ethical and data protection issues necessitate ongoing attention and proactive measures to ensure the responsible and secure deployment of these technologies.

In essence, this paper serves as a valuable resource for researchers and developers in the field of wearable biosensor systems for health monitoring, offering insights into the current landscape, highlighting challenges, and pointing towards future research directions. The transformative impact of these devices on healthcare and daily life is undeniable, and as technology continues to advance, the opportunities for improving health outcomes through wearable biosensor systems are boundless.

References

[1] Bloom DE, Cafiero ET, Jané-Llopis E et al. The global economic burden of noncommunicable diseases. Geneva: World Economic Forum, 2011.

[2] Liu, J.; Liu, M.; Chai, Z.; Li, C.; Wang, Y.; Shen, M.; Zhuang, G.; Zhang, L. Projected rapid growth in diabetes disease burden and economic burden in China: A spatio-temporal study from 2020 to 2030. Lancet Reg. Health–West. Pac. 2023,33, 100700.

[3] Kathirvel, Natarajan (2020). Post COVID-19 pandemic mental health challenges. Asian Journal of Psychiatry.

[4] Anwar A, HvderS, Mohamed Nor N, Younis M. Government health expenditures and health outcome nexus: a study on OECD countries. Frontiers in Public Health. 2023:11:1123759.

[5] Yang, B.; Jiang, X.; Fang, X.; Kong, J. Wearable Chem-Biosensing Devices: From Basic Research To Commercial Market.

[6] Yoon, S. N., Lee, D. H., & Shin, Y. (2020). Innovative Healthcare Wearable Device Usage and Service Enhancement. Global Business & Finance Review 25 (2): 1-10.

[7] Xue, Junwei; Huang, Yueshan; Du, Xin; Wu, Xiuyong; Wu, Kai; Zeng, Weijie; Xi, Yusheng; Chen, Yimin; Zhao, Yu (2015). [IEEE 2015 IEEE 12th Intl Conf on Ubiquitous Intelligence and Computing and 2015 IEEE 12th Intl Conf on Autonomic and Trusted Computing and 2015 IEEE 15th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (UIC-ATC-ScalCom) - Beijing, China (2015.8.10-2015.8.14)] 2015 IEEE 12th Intl Conf on Ubiquitous Intelligence and Computing and 2015 IEEE 12th Intl Conf on Autonomic and Trusted Computing and 2015 IEEE 15th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (UIC-ATC-ScalCom) - Design of a Wearable Device for Monitoring SpO2 Continuously.

[8] Ariyatum, B.; Holland, R.; Harrison, D.; Kazi, T. (2005). The future design direction of Smart Clothing development.

[9] Berglund, Mary Ellen; Duvall, Julia; Dunne, Lucy E (2016). [ACM Press the 2016 ACM International Symposium - Heidelberg, Germany (2016.09.12-2016.09.16)] Proceedings of the 2016 ACM International Symposium on Wearable Computers - ISWC '16 - A survey of the historical scope and current trends of wearable technology applications.

[10] Chang, V., Le Minh T. D., Qianwen A. X., Hall K., Yuanyuan A. W. and Muhammad M. K. (2023). “Digitalization in omnichannel healthcare supply chain businesses: The role of smart wearable devices”,Journal of Business Research.

[11] Francés-Morcillo, L.; Morer-Camo, P.; Rodríguez-Ferradas, M.I.; Cazón-Martín, A. Wearable Design Requirements Identification and Evaluation.

[12] Sun H, Zhang Z, Hu R, Qian Y. Wearable communications in 5G: challenges and enabling technologies. IEEE Veh Technol Mag 2018 Sep.

[13] Fan, Songchun; Llull, Qiuyun; Lee, Benjamin C. (2017). [ACM Press the 18th International Workshop - Sonoma, CA, USA (2017.02.21-2017.02.22)] Proceedings of the 18th International Workshop on Mobile Computing Systems and Applications - HotMobile '17 - Predicting Sensory Data and Extending Battery Life for Wearable Devices.

[14] Sun, H.; Zhang, Z.; Hu, R.Q.; Qian, Y. Wearable Communications in 5G: Challenges and Enabling Technologies. IEEE Veh. Technol. Mag.2018.

[15] Liang, Yeru; Zhao, Chen-Zi; Yuan, Hong; Chen, Yuan; Zhang, Weicai; Huang, Jia-Qi; Yu, Dingshan; Liu, Yingliang; Titirici, Maria-Magdalena; Chueh, Yu-Lun; Yu, Haijun; Zhang, Qiang (2019). A review of rechargeable batteries for portable electronic devices.

[16] El-Amrawy, Fatema; Nounou, Mohamed Ismail (2015). Are Currently Available Wearable Devices for Activity Tracking and Heart Rate Monitoring Accurate, Precise, and Medically Beneficial?

[17] H. Scott, L. Lack and N. Lovato, "A systematic review of the accuracy of sleep wearable devices for estimating sleep onset" in Sleep Med. Rev., vol. 49, Feb. 2020.

[18] Dooley EE, Golaszewski NM, Bartholomew JB. Estimating Accuracy at Exercise Intensities: A Comparative Study of Self-Monitoring Heart Rate and Physical Activity Wearable Devices. JMIR Mhealth Uhealth 2017 Mar 16.

[19] Segura Anaya, L.H.; Alsadoon, Abeer;Costadopoulos, N.; Prasad, P W. C.(2017). Ethical lmplications of UserPerceptions of Wearable Devices.