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The application of conductive hydrogels for self-powered wearable devices: medical field

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Abstract:

Wearable devices are playing an important role in many fields, especially in the medical field, where they are responsible for the detection of vital signals, the quantification of health indicators, and the prevention of diseases. Nowadays, the demand for flexible wearable devices is increasing, and conductive hydrogels (CHs), as an important flexible material, have attracted a lot of attention from researchers because of their excellent properties such as flexibility and bio-adaptability. This paper introduces applications and recent advances of CHs in self-powered devices in the medical field, and divide into two aspects, according to their functions. CHs show excellent potential for applications, especially in human signal detection and biofluid analysis. The versatility of CHs makes them indispensable in the medical field, especially in precision medicine and personalised therapies. Finally, it also discusses the difficulties and challenges still faced by CHs in the integration of wearable devices, as well as the outlook for their future applications and development.

Keywords: Conductive hydrogels, self-powered wearables, medical field.

1. Introduction

Wearable devices have brought great convenience in human daily life, especially in meeting the demand for real-time monitoring of health conditions. With the development of science and technology, smart monitoring devices such as smart watches and smart bracelets are emerging to help users keep abreast of their physiological conditions [1]. However, the application of rigid materials in traditional wearable devices has certain limitations in terms of comfort and durability, especially in the case of prolonged contact with the human body is prone to cause discomfort. To overcome this problem, researchers have developed and integrated a variety of flexible materials to improve the comfort and wearability of devices. Such advances in material technology have not only driven the development of wearable devices, but also opened more possibilities for implantable medical devices [2, 3].

However, traditional wearable devices usually rely on external power supplies and complex circuit designs, which are often rigid, contain toxic substances, and are not easily integrated with the device, which is not conducive to the development and popularisation of microdevices.

Hydrogels have received extensive attention and in-depth research in the biomedical field due to a series of excellent properties, such as tissue similarity, high water content, flexibility, biocompatibility, breathability, self-repairing ability, non-toxicity, and antimicrobial properties [4-6]. The porous structure of hydrogels allows electrons and conductive ions to migrate through them, endowing them with good electrical conductivity, which has led them to show a wide range of applications in bioelectronics [7-9]. In contrast, hydrogels are stretchable and flexible, showing great potential as substrate materials and electrodes for energy conversion, and have been widely used in various types of nanogenerators, such as friction nanogenerators (TENG), piezoelectric nanogenerators (PENG), thermoelectric generators (TEG), biofuel cells (BFC), and hydrovoltaic power generation [10-17]. The application of conductive hydrogels in self-powered wearable devices has also become more and more widespread, covering a wide range of fields such as motion monitoring, health detection, human-computer interaction, and neural stimulation, demonstrating strong functionality and application value [18].

Therefore, the contribution of hydrogel materials in various fields cannot be ignored, especially in the biomedical field. This review will focus on the application of self-powered wearable devices based on conductive hydrogels in medical detection and treatment, and summarise and prospect the future development trend of hydrogels in the medical field.

2. Application in medical detection

Conductive hydrogels (CHs), as a new generation of biomaterials, show excellent potential for applications, especially in human signal detection and biofluid analysis. It is capable of detecting human physiological metabolites such as sweat and blood, as well as monitoring a wide range of biological signals including electrocardiogram (ECG), electromyogram (EMG), and electro-oculogram (EOG) [17]. The excellent properties of CHs make it an ideal material for innovative wearable medical devices, which have shown great promise for health monitoring, therapeutic, and telemedicine applications.

2.1 Body Signal Detection

CHs are able to provide comprehensive health monitoring by detecting electrical signals. For example, a conductive hydrogel with self-adhesive properties possesses excellent stretchability, adhesion and frost resistance. Such CHs can be fabricated by 3D printing and operate in environments as low as -80°C, and are capable of accurately detecting a wide range of biosignals such as electrocardiograms, electrooculograms, and electromyograms [19]. This property makes the CHs particularly suitable for physiological signal detection in extreme environments.

In order to improve the detection of EEG signals, researchers designed an electrode based on soft ionic hydrogel. The claw and patch structure of this electrode solves the problems of skin friction and long preparation time caused by traditional wet electrodes and avoids the electrode falling off after use [20]. Meanwhile, the modified hydrogel was doped with glycerol, which significantly improved its moisturising properties and comfort of use. These electrodes can not only be placed in air for a long period of time, but also have high mechanical properties, which are highly potential for application in daily wear and long-term high-precision electroencephalography (EEG) signal acquisition, as shown on Fig. 1A [21].

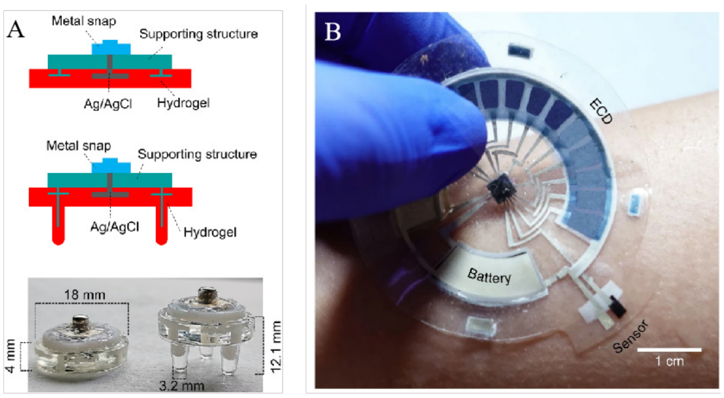

Fig. 1 CHs for body signal detection. (A) Schematic diagram of the planar hydrogel Electrode for EEG signal [21]. (B) All-printed skin-interfaced ECD sensing patch [22].

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However, traditional hydrogel sensors have insufficient adhesion and often suffer from unstable signal acquisition during wear. To address this challenge, scientists borrowed the layered structure of human skin and developed a sensor with a sandwich structure containing an adhesive, conductive, and elastic layer. Through glycerol doping, CHs exhibit excellent elasticity and adhesion in the sensor, while their unique crack response mechanism enables the sensor to achieve high precision detection during both large movements (e.g., knee movement and finger bending) and small movements (e.g., throat vibration and heart rate). Such sensors are promising for the development of wearable devices in the fields of e-skin and healthcare [23].

In rehabilitation after laryngeal surgery, it is important to detect and assess swallowing ability and vocal cord movement. Unlike traditional bulky and rigid devices, a fully integrated telescopic device has been designed for long-term monitoring of electrical signals from laryngeal muscles. With low contact impedance and low-adhesion CHs, the device enables high-quality detection of electrical signals and is easily removable. A three-axis broadband accelerometer and functional electronics are integrated in the device to enable continuous, non-invasive body signal monitoring via wireless signal transmission, an innovation that opens up new possibilities for remote diagnosis for disease prediction and postoperative rehabilitation [24].

2.2 Biofluid detection

In the field of biofluid detection, conductive hydrogels have also demonstrated their excellent potential for application. While conventional wearable devices still face challenges in data visualisation and energy supply, a novel sweat sensing platform successfully addresses this challenge by integrating sensors, stretchable batteries and low-power digital electrochromic displays. This platform utilises a polyvinyl alcohol (PVA) hydrogel as the electrolyte interface, which is highly biocompatible and flexible, and is capable of accurately detecting sodium ion concentration and pH in sweat and maintaining excellent performance during multiple cycles of use and stretching, as shown on Fig. 1B [22]. Such devices are expected to be widely used in personal health management and medical monitoring.

In addition, fluctuations in cortisol levels are important for understanding the human stress response. A non-invasive haptic-based molecularly imprinted polymer (MIP) device is capable of detecting cortisol in fingertip sweat in a highly selective manner. The device uses a highly permeable PVA hydrogel with a low impedance and porous structure to enable rapid collection of sweat samples and label-free electrochemical detection by embedding a Prussian blue redox probe. This device is easy to operate and can rapidly capture dramatic changes in cortisol levels, providing a new solution for stress and mental health management [25,26].

Sleep disorders, as a chronic condition, often require long-term monitoring and treatment, and real-time monitoring of sleep apnoea in particular is crucial. Researchers have developed a respiration detection system based on a dual-network hydrogel that has different electrical conductivity under different humidity conditions, which is particularly suitable for remote respiratory monitoring. The system is integrated into a mask that enables real-time monitoring of the patient's respiratory status via wireless circuits, and the device automatically sends out an alert when a respiratory interval of more than 10 seconds is detected. Such a system provides a convenient home monitoring and treatment option for sleep apnoea patients [27].

2.3 Discussion

Conductive hydrogels, as a promising material for a wide range of applications, have made important breakthroughs in the fields of health monitoring and biosignal acquisition. By continuously optimising their mechanical properties, electrical conductivity and biocompatibility, conductive hydrogels provide an important technological foundation for the development of future wearable devices. Whether it is the monitoring of ECG and EEG signals, or the analysis of sweat and other biological fluids, CHs show great potential. With further technological development, conductive hydrogels are expected to provide more innovative solutions for personalised medicine, remote diagnosis and health management in the future.

3. Therapeutic applications

As a biocompatible and structurally flexible material, conductive hydrogels (CHs) are increasingly being used in various medical applications. Not only are they able to adapt to the biological environment and remain flexible, but they can also be integrated into miniature medical devices, giving them significant advantages in drug delivery, wound healing, etc. The versatility of CHs makes them indispensable in the medical field, especially in precision medicine and personalised therapies. Next, the applications of conductive hydrogels in drug delivery and wound healing will be discussed in depth.

3.1 Drug Delivery

The development of drug delivery systems is important in the medical field to improve drug utilisation, reduce side effects and enable on-demand drug delivery. In this field, the use of hydrogels has shown significant advantages, especially in minimally invasive treatments and local drug delivery.

Dental patch drug delivery systems

Dental caries (tooth decay) is a global public health problem that can lead to serious complications if left untreated for long periods of time. To address this problem, scientists have developed a battery-free, wearable dental patch system based on conductive hydrogel. The system integrates Polyaniline (PANi), Polypyrrole (PPy), and a near-field communication (NFC) antenna, and uses electrochemical detection of the acidic environment in the oral cavity and local drug delivery based on the results. When the acidic microenvironment in the oral cavity due to bacterial metabolism is detected, PPy is electrically stimulated as a drug carrier to release fluoride to prevent further deterioration of dental caries. Such a system not only monitors the oral environment in real time, but is also capable of delivering precise treatment as needed, demonstrating great clinical potential [28].

Smart contact lenses

Diabetic retinopathy is one of the common complications in diabetic patients, and in order to provide early diagnosis and effective treatment for this condition, researchers have developed a smart contact lens. The contact lens, which is embedded with sensors, a drug delivery system and a wireless energy transmission module, is able to predict fluctuations in a patient's blood glucose by continuously monitoring glucose levels in tears. The system uses a conductive hydrogel as a sensing interface to store medication and determine the timing of its release based on real-time data. In the experiment, this smart glasses successfully achieved non-invasive diabetes detection and retinopathy treatment, providing a new treatment option for diabetic patients [29].

3.2 Self-healing hydrogel wound dressing

In wound healing, hydrogels not only provide a good barrier function, but also serve as a storage and delivery platform for drugs. A self-healing hydrogel based on quaternised chitosan (QCS) and Pluronic F127 (PF127-CHO) capped with benzaldehyde was developed as a wound dressing for joint skin injuries. The hydrogel was able to release drugs as needed and exhibited good mechanical strength and biocompatibility during wound healing. This hydrogel contains Curcumin (curcumin) which plays a significant role in accelerating the wound healing process and greatly facilitates the regeneration of skin tissue [30].

3.3 Wound care

Conductive hydrogels also play an important role in wound care, as their soft and porous structure not only provides good protection for wounds, but also keeps wounds moist, promotes healing, and has the ability to be integrated with other functional modules, such as electrical stimulation and real-time monitoring systems.

3.3.1 Electrical Stimulation for Wound Healing

During the wound healing process, an endogenous electric field guides cell migration and promotes tissue regeneration through Na/K ion transport. Based on this principle, the researchers have designed a self-adhesive patch based on conductive hydrogel that integrates piezoelectric nanogenerators to generate electrical stimulation as the wearer moves, further accelerating wound healing.The HPSP (Hydrogel-Piezoelectric Skin Patch) uses a hydrogel matrix inspired by mussels to optimise the skin's adaptation. This patch has shown significant ability to promote wound healing in animal studies and is particularly suitable for accelerated treatment of skin wounds [31].

3.3.2 Wearable wound care devices

Conductive hydrogels can be integrated with electronic systems for the development of wearable wound monitoring devices due to their flexibility and conductivity. For example, adhesive electrodes are capable of conducting electrical signals in wound care, but the lack of adhesion of conventional electrodes may lead to secondary wound damage. To address this issue, the researchers designed a wirelessly powered system with closed-loop sensors and stimulation circuits and used hydrogel electrodes with a thermally controlled reversible phase change mechanism. This PEDOT:PSS (poly(3,4-ethylenedioxythiophene))-based hydrogel demonstrated good biocompatibility and was able to provide stable electrical stimulation and monitoring during faster wound healing, with a 25% increase in healing speed [32].

3.3.3 Diabetic ulcer monitoring and treatment

Diabetic ulcers are chronic wounds that are difficult to heal and often lead to serious complications, even requiring amputation. To address this challenge, scientists have developed a smart wound dressing with an integrated sensor system that monitors key metrics such as temperature, strain, and glucose levels. The conductive hydrogel layer in this system is not only biocompatible, but also able to monitor the progress of diabetic ulcers in real time and provide timely feedback to doctors through data transmission. The application of this smart dressing significantly improves the quality of wound care for diabetic patients and reduces the risk of infection [33].

3.3.4 Lactate testing for wound healing assessment

During the wound healing process, lactic acid, as a prod-

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uct of metabolism, can reflect the healing of tissues. Based on this, researchers have developed a miniaturised lactate detector that seamlessly integrates with the bandage and transmits data wirelessly via NFC protocol. The application of conductive hydrogel allowed the device to be attached to the wound site for a prolonged period of time and achieve up to 76% accuracy in lactate detection within 3 days. This real-time assessment system can not only help predict wound healing progress, but also provide a personalised care plan for patients with chronic wounds such as diabetic foot [34].

4. Challenge and future trend

In recent years, the development of flexible wearable devices has gained momentum as the limitations of rigid wearable devices are gradually exposed. As a flexible and highly adaptable material, hydrogel has attracted more and more researchers' attention due to its excellent biocompatibility, electrical conductivity, and structural flexibility. The plasticity and tunability of conductive hydrogels make them ideal for self-powered wearable devices, especially in the medical field, where their applications are extremely promising. From drug delivery, wound healing to biosignal detection, hydrogels have made significant progress in a variety of clinical applications and are gradually entering the practical application stage.

Although the research and application of conductive hydrogels have begun to bear fruit, there are some key issues that need to be addressed in order to achieve a wider range of medical applications. First of all, conductive hydrogel in the long-term use of stability and environmental adaptability still need to be further improved. Wearing the device for a long time exposed to the external environment, affected by temperature, humidity and mechanical stress, the mechanical properties of the hydrogel may gradually decline, affecting its functional performance in bioelectronic devices. Researchers are exploring various methods, such as introducing new polymers or nanomaterials, to enhance the adaptability and durability of hydrogels in different environments.

Secondly, the detection sensitivity and selectivity of conductive hydrogels is still a technical bottleneck that needs to be broken through. In the field of biomonitoring, hydrogels are often used to detect signals in organisms, such as electrophysiological signals, metabolites or drug release levels. However, it is a great challenge to accurately identify and differentiate target signals in complex biological environments. For example, sensors may need to respond to extremely weak electrical signals or chemical changes, and the sensing sensitivity of hydrogels has not yet reached the desired level in these cases. Therefore, future research needs to focus on improving the signal detection ability of conductive hydrogels and developing efficient signal amplification and filtering mechanisms.

In addition, the recycling, degradation, and biosafety issues of hydrogel materials are still one of the factors limiting their large-scale applications. Although the biocompatibility of hydrogel materials is widely recognised, their long-term stability in the human body and the potential health effects of their products of degradation in the body need to be thoroughly investigated. In addition, the degradability and recyclability of hydrogel materials are increasingly becoming a research priority with the growing global concern for environmental sustainability. The development of hydrogel materials that can be safely degraded or easily recycled at the end of the life cycle of medical devices is an important direction for future research.

5. Conclusion

It is foreseeable that future medical devices will be smarter, miniaturised and more personalised, and the unique properties of conductive hydrogels will provide strong support for these innovations. Whether in chronic disease management, wound care, or precise biosignal detection, conductive hydrogels are expected to revolutionise medical technology. The application of self-powered wearable devices based on conductive hydrogels in the medical field has made significant progress, and its future development potential cannot be ignored. Although there are still some technical difficulties at this stage, such as material stability, signal detection ability and environmental friendliness, with the continuous breakthroughs in related technologies, the prospects for the application of hydrogel in medical wearable devices will be broader. Researchers need to continue in-depth research and development of new materials and technologies to meet the current challenges and drive the field into more practical application scenarios. With the application of new technologies and continuous innovation, self-powered wearable devices based on conductive hydrogels are expected to further advance the realization of personalised medicine and provide more efficient and convenient treatment options for patients.

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