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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 increasingly important role in various fields, particularly in healthcare. These devices not only detect vital signs but also quantify health indicators and thus play a crucial role in disease prevention. The demand for flexible wearable devices continues to rise. In this context, conductive hydrogels (CHs) have emerged as a novel flexible material that has garnered significant attention from researchers due to its excellent flexibility and biocompatibility. This article will focus on the applications and recent advancements of conductive hydrogels in the medical field, particularly in self-powered devices. Based on their functions, the applications can be categorized into two main areas: medical detection and treatment. In the realm of medical detection, conductive hydrogels can monitor physiological signals in real-time, such as electrocardiograms (ECG), electromyograms (EMG), and skin temperature. Researchers have successfully combined conductive hydrogels with flexible electrodes to achieve highly sensitive signal acquisition. This technological advancement enables long-term monitoring, greatly enhancing patient comfort and convenience. In terms of treatment, conductive hydrogels are applied in electrical stimulation therapies and drug delivery systems. They not only effectively conduct electricity but also can interact with drugs to achieve precise therapeutic effects. Despite their promise, challenges remain, including long-term stability, material integration, and scaling up manufacturing processes. Overall, the future of conductive hydrogels in wearable devices is promising, poised to advance personalized medicine and smart health management.

Keywords: Conductive hydrogels; Self-powered wearables; Biomedical engineering.

1. Introduction

Wearable devices have significantly enhanced convenience in daily life, particularly by addressing the growing demand for real-time health monitoring. Devices such as smartwatches and fitness trackers are prime examples of intelligent detection systems that empower individuals to monitor their health metrics on the go, with significant advancements in both technology and user adoption over recent years [1]. To further enhance the performance and comfort of wearable technologies, innovations in flexible materials have emerged, addressing challenges such as the rigidity of traditional materials. These innovations have also catalyzed the development of implantable devices, expanding the possibilities for medical applications and continuous health monitoring [2, 3]. Among the materials making strides in this area, hydrogels have garnered considerable attention due to their unique properties. Hydrogels, which have been widely researched and utilized in the biomedical field for decades, offer a tissue-like structure that closely mimics the natural human body. Their impressive attributes—including high water content, flexibility, biocompatibility, air permeability, self-healing abilities, non-toxicity, and antimicrobial properties—make them ideal candidates for both wearable and implantable devices [4-7]. Moreover, the porous structure of hydrogels allows for the migration of electrons and conductive ions, thus transforming them into excellent conductive materials with extensive applications in bioelectronics [8-10]. Traditional wearable devices, despite their growing sophistication, often face challenges related to bulky external power supplies and intricate circuit designs. The use of rigid and sometimes toxic materials can hinder device miniaturization, integration, and sustainable power supply, which are essential for the future of wearable technology [11-14]. In contrast, hydrogels, with their stretchable and flexible nature, offer promising alternatives for substrates and electrodes used in energy conversion processes. They have found practical applications in triboelectric nanogenerators (TENG), piezoelectric nanogenerators (PENG), thermoelectric generators (TEG), biofuel cells (BFC), and hydrovoltaic devices, all of which are integral to self-powered wearable technologies [15-17]. Conductive hydrogels, specifically, have revolutionized self-powered wearable devices, making them crucial across various domains, such as motion monitoring, health diagnostics, human-computer interaction, and neural stimulation [18].

This review aims to explore the pivotal role of conductive hydrogel-based self-powered wearable devices, with a focus on their biomedical applications. The discussion will be organized into two main areas: medical diagnostics and therapeutic applications. Finally, the latest advances in the field will be summarized and insights into the future potential of hydrogels in medical technology will be provided.

2. Application in Medical Detection

Conductive hydrogels (CHs) can be utilized to monitor a variety of human physiological metabolites, such as sweat and blood. Additionally, they are capable of detecting human bio-signals, including electrocardiograms (ECG), electromyograms (EMG), and electrooculograms (EOG), etc. [17]. These capabilities make CHs highly promising for applications in health monitoring and medical diagnostics.

2.1 Physical Signals Detection

A self-adhesive conductive hydrogel exhibits remarkable characteristics, including exceptional stretchability, strong adhesive properties, and outstanding anti-freezing capability (Fig. 1A) [19]. This type of conductive hydrogel (CH) can be fabricated through advanced 3D printing techniques, allowing for precise customization of its structure [19]. Notably, it is capable of detecting bio-signals such as electrocardiograms (ECG), electrooculograms (EOG), and electromyograms (EMG) even under extreme conditions, functioning effectively at temperatures as low as -80°C [19]. These properties make it highly suitable for applications in harsh environments and advanced biomedical monitoring systems.

Researchers have developed soft ionic-hydrogel-based electrodes, which were designed in innovative claw-like and patch-like structures [20]. When used for measuring electroencephalogram (EEG) signals, these electrodes effectively address the limitations commonly associated with traditional wet gel electrodes [20]. Specifically, they eliminate issues such as skin abrasion and the longer preparation time required for application [20]. Additionally, they prevent the problem of electrode detachment after use, offering a more reliable and user-friendly solution for EEG monitoring [20]. Building upon this, researchers have developed a hydrogel mixed with glycerin, known for its excellent moisturizing properties [21]. This advanced formulation significantly reduces skin abrasion and enhances the ease of electrode installation (Fig. 1B) [21]. Due to its ability to remain effective when exposed to air for extended periods and its high mechanical strength, this hydrogel shows substantial promise for daily wear and long-term, high-precision EEG acquisition [21]. Its durability and comfort make it particularly suitable for continuous and extended use in various monitoring applications.

Traditional hydrogel sensors often face challenges related to convenience and signal acquisition due to their insufficient adhesive properties [22]. Flexible sensors made from viscous hydrogels can also be affected by various impurities, leading to issues with data acquisition sensitivity and accuracy [22]. To address these limitations, researchers have designed a sensor with a sandwich-like layered structure inspired by the stratified composition of human skin (Fig.1C) [22]. This innovative sensor features three distinct layers: an adhesive layer, a conductive layer, and an elastic layer [22]. The conductive hydrogel (CH) used in this sensor is doped with glycerol, enhancing both its elasticity and adhesive properties [22]. The sensor's unique crack response mechanism contributes to its high sensitivity, enabling it to accurately detect a wide range of movements [22]. It can recognize both large movements, such as knee flexion and finger bending, as well as subtle motions, like throat vibrations and heart rate variations [22]. This advanced sensor holds significant promise for applications in the development of electronic skin and wearable devices designed for healthcare monitoring, offering a reliable solution for both daily and high-precision tracking needs.

Accurate detection and evaluation of recovery progress, swallowing ability, and vocal cord movement following laryngopharyngeal surgery are crucial for effective postoperative care [23]. To address the limitations of traditional rigid and bulky devices, a fully integrated, standalone stretchable device (Fig. 1D) has been designed and validated for this purpose [23]. This innovative device features a conductive hydrogel (CH) with low contact impedance and minimal adhesion force, enabling high-quality, long-term monitoring of local muscle electrical signals [23]. The improved composite hydrogel electrode interface ensures a secure yet comfortable contact with the throat, offering a low adhesion force that allows for easy removal when necessary [23]. In addition to the hydrogel electrodes, the device incorporates an integrated triaxial broadband accelerometer and advanced functional electronics [23]. These components enable the continuous and noninvasive transmission of processed signals wirelessly, facilitating real-time monitoring of bodily functions [23]. This technology significantly enhances the capabilities for remote diagnosis, monitoring, and evaluation, supporting both disease prediction and postoperative rehabilitation. By providing accurate and convenient assessments, it represents a substantial advancement in patient care and recovery management.

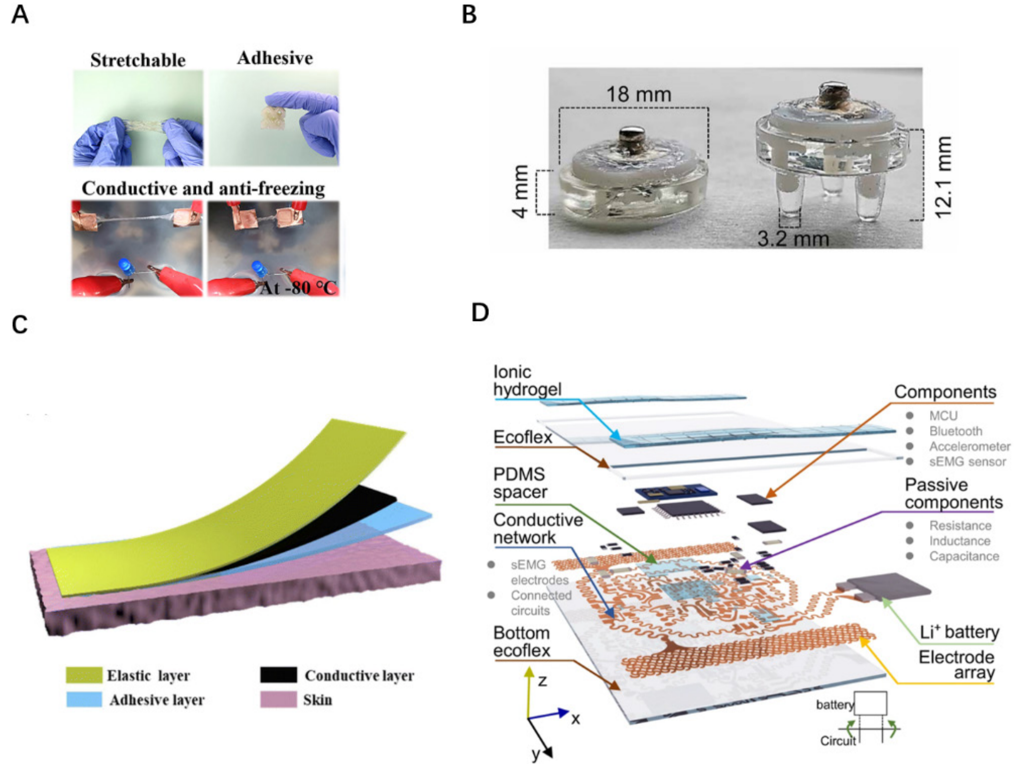

Fig. 1 The application in medication detection for physical signals detection. (A) The exhibition of a stretchable, adhesive, conductive and anti-freezing hydrogel [19]. (B) Photo of the planar hydrogel electrode (left) and columnar hydrogel electrode (right) [21]. (C) Schematic illustration of the sensor [22]. (D) Exploded diagram of the integrated device system [23].

2.2 Biofluid Detection

Wearable devices often face the challenge of needing external connections for power supply and data visualization when monitoring human health data. To address this issue, a novel independent sweat sensing platform (Fig. 2A) has been developed [24]. This platform integrates essential components, including sensors, a stretchable battery, and a low-power digital electrochromic display, into a cohesive system [24]. The platform employs polyvinyl alcohol (PVA) hydrogel as the electrolyte interface, chosen for its high biocompatibility and flexibility [24]. This hydrogel supports the detection of sodium ion concentration and pH levels in sweat effectively. It maintains excellent performance even during prolonged sensing and stretching cycles, ensuring reliability. This advanced sweat sensing platform offers a practical solution for continuous health monitoring, enabling real-time data collection and visualization without the need for external devices. Its design makes it suitable for both personal health management and medical monitoring applications.

Understanding the fluctuation of cortisol levels is crucial for evaluating the body's response to stress [25]. A touch-based non-invasive molecularly imprinted polymer (MIP) device (Fig .2B) has been developed to reliably detect cortisol levels in fingertip sweat with high selectivity [25]. This innovative device utilizes a highly permeable polyvinyl alcohol (PVA) hydrogel, which offers low impedance and a porous structure, allowing for rapid and efficient sweat collection [25]. The MIP network integrates Prussian blue redox probes, enabling sensitive label-free amperometric detection of cortisol [25]. The device is designed to be user-friendly, capturing sharp changes in cortisol levels by minimizing time lags [25]. In addition to monitoring cortisol, it can also indicate other conditions such as injury, fatigue, and dehydration through its integrated platform [25]. This device plays a significant role in personal stress management and mental health monitoring, providing valuable insights into an individual's stress response and overall well-being.

In most cases, sleep disorders are a chronic disease that requires continuous treatment and monitoring [26]. And sleep apnea can lead to a variety of diseases and accidents, including high blood pressure and cardiovascular disease [26]. At the same time, sleep monitoring requires real-time recording and prolonged treatment, making it difficult to meet the demand for hospital and private care [26]. At this time, it is particularly important to develop remote monitoring and treatment, which can support patients to conduct long-term wireless treatment and recording in the home environment [26]. The dual-network hydrogel based on polyacrylamide groups showed different electrical conductivity under different humidity conditions [27]. In the high humidity environment, the hydrogel contains a large number of unbonded hydrophilic groups, so it has a strong adsorption effect on water molecules, which increases the concentration of ions, i.e. charge carriers [27]. The swell effect also reduces the obstacles to ion migration, and finally increases the ion mobility and improves the conductivity [27]. Researchers have integrated this CH with masks (Fig. 2C) and wireless circuits to develop a remote breathing detection and alarm system, which can alarm patients when their breathing interval exceeds 10 seconds [27].

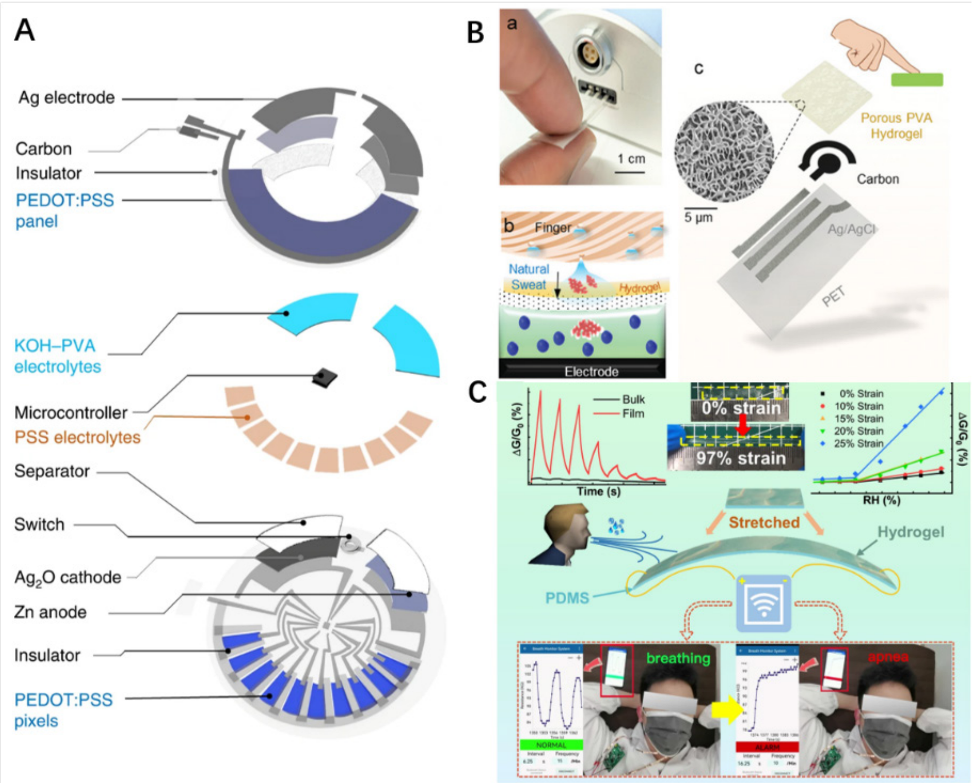

Fig. 2 The application in signal detect for biofluid detection. (A) Exploded view detailing the individual layers of the epidermal patch [24]. (B) The touch-based fingertip cortisol sensor includes: a) photographs showcasing the application of the single-touch sensor; b) an illustration depicting the sensing mechanism; and c) a structural illustration of the fingertip cortisol sensor, featuring a cryogenic scanning electron microscopy image of the porous PVA hydrogel [25]. (C) Schematic diagrams and photographs illustrate the exceptional performance of the stretchable hydrogel film humidity sensor, highlighting its practical application for wireless respiration monitoring in wearable devices [27].

3. Application in Therapy

Hydrogels have made significant contributions to medical treatment due to their remarkable properties. Their excellent biocompatibility allows them to seamlessly adapt to the biological environment, making them highly suitable for various medical applications. The inherent flexibility of hydrogels enables their easy integration into a wide range of small medical devices, which is particularly beneficial in fields such as drug delivery and wound healing. In drug delivery, hydrogels can be used to create controlled release systems that ensure medications are delivered at a steady rate over time. For wound healing, their moisture-retentive properties support the healing process by creating an optimal environment for tissue regeneration. Overall, hydrogels continue to play a crucial role in advancing medical technologies and improving patient care.

3.1 Drug Delivery

Dental caries represents a significant yet often overlooked global public health challenge, potentially leading to severe toothache, sepsis, and even tooth loss if not addressed [28]. To tackle this issue, a miniaturized, battery-free wearable dental patch system (Fig. 3A) has been developed [28]. This innovative system utilizes unlimited energy harvesting and data transmission capabilities to monitor and respond to the acidic microenvironment caused by bacterial metabolism in the oral cavity [28]. The system integrates several advanced components, including polyaniline (PANi), polypyrrole (PPy), and Near Field Communication (NFC) antennas [28]. Both PANi and PPy are chosen for their biocompatibility, stability, and excellent electrical properties [28]. PANi-based biosensors are employed to detect any abnormalities in the oral environment, while the PPy-based drug carrier responds to these signals by releasing fluoride immediately [28]. This approach enables timely and on-demand treatment, effectively addressing the acidic conditions and preventing the progression of dental caries [28]. The system's ability to provide localized treatment and continuous monitoring represents a significant advancement in dental care and oral health management [28].

After establishing a strong correlation between glucose levels in blood and tears, a smart contact lens has been developed for continuous glucose monitoring and treatment [29]. This advanced contact lens incorporates several key components: a sensor, a drug delivery system, an unlimited energy transfer mechanism, a power management unit, and a communication system [29]. The sensor uses glucose oxidase and bovine serum albumin immobilized in a chitosan (CS) and polyvinyl alcohol (PVA) hydrogel [29]. This setup is designed to monitor glucose levels and manage diabetic retinopathy by releasing medication from a reservoir [29]. The system also includes a wireless power supply and communication system to relay data effectively [29]. Experimental trials conducted on rabbit eyes have demonstrated the feasibility of this noninvasive approach for continuous diabetes monitoring and treatment of diabetic retinopathy (Fig. 3B) [29]. This smart contact lens represents a significant advancement in wearable medical technology, offering a practical solution for managing diabetes and associated eye conditions.

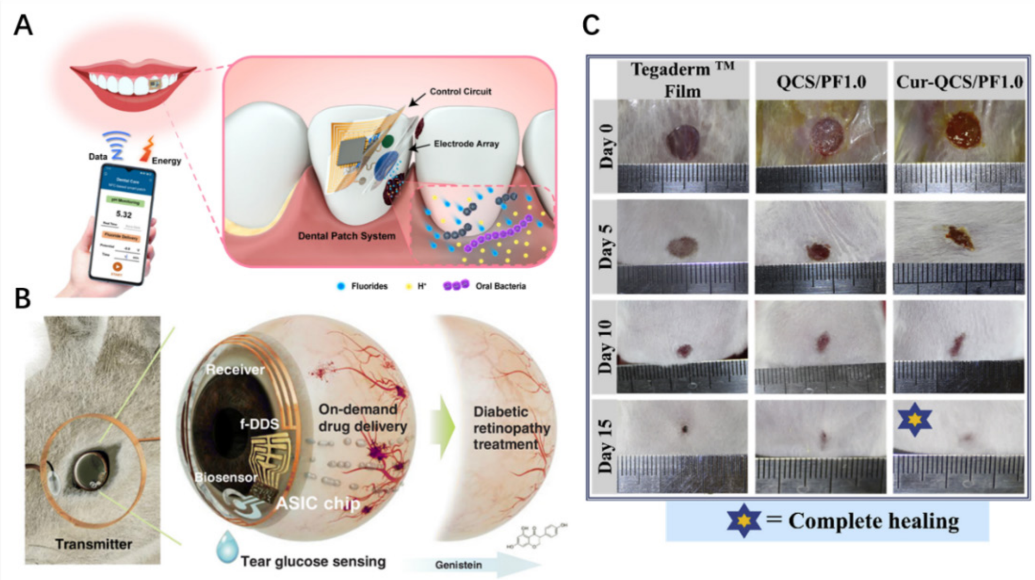

Fig. 3 The application in therapy for drug delivery. (A) A schematic of the dental patch system includes the control circuit and the electrode array, designed for in situ monitoring of the oral microenvironment and facilitating on-demand drug delivery [28]. (B) Schematic illustration for in vivo diabetic diagnosis and therapy of the smart contact lens [29]. (C) Photographs depicting wounds at the 0th, 5th, 10th, and 15th days are shown for the commercial film dressing (Tegaderm™) as the control, alongside the QCS/PF1.0 hydrogel and the Cur-QCS/PF1.0 hydrogel [30].

A self-healing, multifunctional injectable micellar/hydrogel composite has been developed for use as a wound dressing, particularly for joint skin injuries, and for facilitating on-demand drug delivery [30]. This innovative composite integrates chitosan (QCS) with quaternary ammonium and benzaldehyde-modified pluronic F127 (PF127-CHO) [30]. The resulting QSC/PF1.0 hydrogel is further enhanced with curcumin, Cur-QCS/PF1.0 hydrogel, which contributes to its therapeutic capabilities (Fig. 3C) [30]. The composite hydrogel demonstrates excellent biological compatibility, robust chemical stability, and favorable mechanical properties [30]. Its self-healing characteristics ensure that it can maintain its integrity and functionality even after being subjected to mechanical stress [30]. The hydrogel shows exceptional performance in wound healing, significantly accelerating the healing process and providing an effective solution for managing joint skin injuries [30]. This multifunctional approach not only supports wound repair but also enables controlled drug release, enhancing overall treatment efficacy.

3.2 Wound Treatment

Sodium/potassium (Na/K) ion transport generates an endogenous electric field (EF) that directs skin cells to migrate towards the wound, thus promoting the wound healing process [31]. Building on this research, electrical stimulation therapy has been introduced as a strategic method to enhance wound healing outcomes [31]. In this context, a bioinspired hybrid patch featuring a self-adhesive design and a piezoelectric nanogenerator (HPSP) has been developed to enhance skin wound healing [32]. The HPSP features a mussel-inspired hydrogel matrix [32]. This matrix is optimized for both post-modulus and permeability, making it highly compatible with the skin [32]. The HPSP functions as a wearable device capable of delivering electrical stimulation to the wound site [32]. Its innovative design not only adheres securely to the skin but also provides continuous stimulation, thereby supporting and accelerating the healing process (Fig. 4A) [32]. This patch represents a significant advancement in wound care, combining mechanical, biological, and electrical properties to improve healing efficacy.

Hydrogels are highly effective in wound treatment due to their excellent porous structure and good air permeability [33]. These characteristics help maintain optimal moisture levels and ensure adequate ventilation in the wound area [33]. By providing a moist environment, hydrogels facilitate faster healing and reduce the risk of infection. Their ability to manage both hydration and air flow significantly supports the wound healing process, contributing to a more efficient and effective recovery [33]. Adhesive electrodes are effective in transmitting stable signals, but they often pose a challenge due to their adhesive force [34]. When these adhesive dressings detach, they can cause secondary wounds, complicating the healing process [34]. To address this issue, A wire-powered system with closed-loop sensor and stimulation circuit was developed (Fig. 4B), and with hydrogel electrodes that can adhere and separate on demand [34]. This system utilizes hydrogel electrodes that can adhere and detach on demand, mitigating the risk of secondary injuries [34]. The hydrogel used in this system is composed of poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT: PSS) hydrogel, which is known for its excellent biocompatibility [34]. This hydrogel incorporates a thermally controlled reversible phase transition mechanism within its scaffold structure [34]. This innovative approach allows the hydrogel to switch between adhesive and non-adhesive states based on temperature changes, providing flexibility in its application [34]. Compared to traditional methods, this system has demonstrated a 25% faster wound healing rate in experimental settings [34]. This improvement highlights the effectiveness of integrating advanced hydrogel technology with a responsive, wire-powered system to enhance wound care and accelerate recovery.

Diabetic ulcers represent a significant challenge as chronic wounds that are often difficult to heal [35]. These ulcers can lead to serious complications, including the risk of amputation, a range of health issues, and in severe cases, even death [35]. The persistent nature of diabetic ulcers not only impacts the patient’s quality of life but also places a considerable burden on healthcare systems [35]. Effective management and innovative treatment strategies are essential to address these complications and improve patient outcomes. Monitoring and diagnosing the microenvironment of diabetic wounds is crucial for effective management and treatment [36]. To address this need, researchers have developed a zwitterionic skin sensor system (Fig. 4C) capable of distinguishing between temperature, strain, and glucose concentration [36]. This system utilizes a hydrogel that is sensitive to zwitterionic thermo-glucose interactions, providing precise measurements of these critical parameters [36]. Building on this technology, a smart wound dressing has been created to monitor and differentiate between infection, swelling, and blood glucose levels [36]. This advanced dressing integrates the zwitterionic sensor system, enabling continuous and real-time assessment of the wound’s condition [36]. By providing detailed information on various aspects of the wound environment, the smart dressing facilitates better monitoring and more effective healing for patients with diabetic ulcers, ultimately improving patient outcomes and management strategies [36].

Hydrogel bioelectronics offer valuable support in predicting wound healing progress [35]. Lactic acid plays a significant role in initiating the healing process, and researchers have developed a miniaturized wound detector that leverages NFC (Near Field Communication) protocol for wireless data transmission [35]. This device is designed for seamless integration with bandages, enhancing its practicality and usability. The hydrogel-based detector is capable of real-time lactate detection, providing crucial insights into the wound’s condition [35]. Initially, the device achieves an accuracy of 76% within the first three days of use [35]. After subsequent modifications, this accuracy improves to 83% [35]. Such real-time assessment and predictive capabilities are instrumental in reducing the health risks associated with diabetic foot ulcers [35]. Moreover, this advanced technology not only helps in monitoring and managing wounds more effectively but also contributes to understanding wound healing mechanisms (Fig. 4D) [35]. It paves the way for the development of innovative wound care products and strategies, offering promising solutions for improving patient care and treatment outcomes.

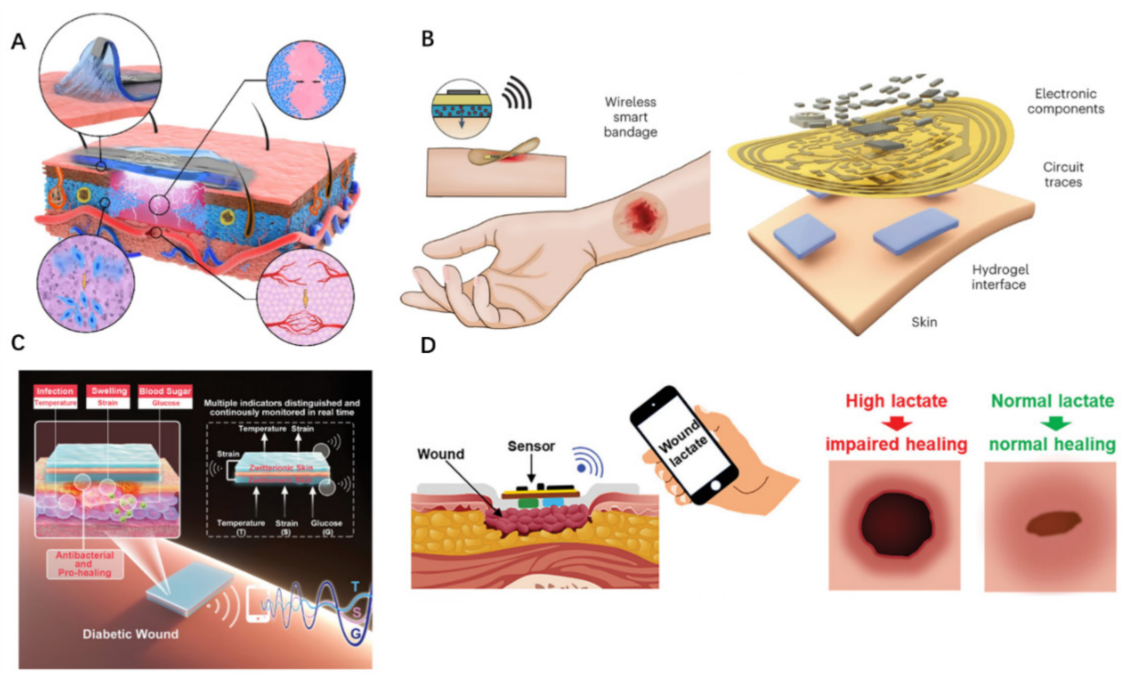

Fig. 4 The application in therapy for wound treatment. (A) Possible mechanism of the HPSP promoting [32]. (B) Schematic diagram (left) and exploded view (right) of the wireless smart bandage including flexible printed circuit board (FPCB) and tissue-interfacing conducting adhesive hydrogel [34]. (C) Scheme illustration of the sandwich-structured sensor based on multi-response zwitterionic skin for multiple sensation and pro-healing of diabetic wounds [36]. (D) A wireless, battery-free wound lactate monitor is designed for predicting wound closure. The schematic representation illustrates the wireless monitoring of wound lactate levels and highlights its potential application in identifying impaired healing [35].

4. Conclusion

In recent years, in response to the shortcomings of hard-wearing devices, flexible wearable devices are booming. As a highly adaptable and ideal flexible material, hydrogel has received extensive attention and research, the integration of hydrogels into a variety of self-powered wearable devices has made some progress and has been put into practical applications to a certain extent. More and more attention has been paid to the research of hydrogel materials in wearable devices in the medical field. Hydrogel materials not only extend the traditional biological monitoring function, but also show great advantages in wound treatment and drug delivery. Hydrogel materials have become candidates with great potential in bioelectronics and provide great possibilities for the development of wearable devices.

However, the practical application of hydrogel materials still faces the following difficulties: (1) The stability of conductive hydrogel in long-term use needs to be further improved, and its adaptability to the environment needs to be strengthened. (2) The detection sensitivity and selectivity to target signals of conductive hydrogels are still a challenging task. (3) The recycling, degradation, and safety of conductive hydrogel materials still need to be explored.

In summary, certain progress has been made in self-powered wearable devices based on conductive hydrogels in the medical field. In the future, researchers still need to overcome the current difficulties and continue to research and develop related technologies. It is foreseeable that there will be more possible practices and applications in this field in the future.

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