Research Progress on Hydrogel-Based Multifunctional Sensors for Health Monitoring

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Abstract. Hydrogel-based sensors (HBS), as core devices at the intersection of flexible electronics and biomedical engineering, exhibit great application potential in areas such as human motion detection and health monitoring due to their excellent mechanical properties, conductivity, high sensitivity, and biocompatibility. This paper first explains the research progress of HBS, focusing on the intrinsic relationships among material design, structural optimization, performance regulation, and application scenarios. It then examines the sensing mechanisms, advantages, disadvantages, and application fields of four types of sensors: resistive, capacitive, piezoelectric, and triboelectric, with a focus on their materials and structures. By introducing polymer materials such as polyacrylamide (PAM), poly (2-acrylamide-2-methylpropanesulfonic acid) (PAMPS), and polyvinyl alcohol (PVA); polysaccharide materials like alginate, cellulose, and chitosan (CS); as well as conductive fillers such as MXene, carbon nanotubes, polypyrrole (PPy), and polyaniline (PANI), strategies for regulating electron and ion migration behaviors have been implemented. Through the construction of double-network (DN) or interpenetrating polymer network (IPN) structures, HBS with excellent mechanical properties, conductivity, anti-swelling performance, transparency, and biocompatibility have been developed. These sensors have been successfully applied in wearable and implantable scenarios, including human motion detection (e.g., pulse monitoring, joint motion tracking, facial expression recognition) and health monitoring (e.g., powering cardiac pacemakers, sweat analysis). Starting from the diverse sensing mechanisms of HBS, this paper provides a detailed summary of the construction principles, diversified material regulation, motion mode detection, and implantable sensing applications of HBS-based bioelectrical medical monitoring systems. Finally, the development prospects of HBS-based bioelectrical medical monitoring systems are discussed.

Keywords: Hydrogel; Flexible Sensor; Motion Detection; Health Monitoring.

1. Introduction

With the deep integration of flexible electronic technology and biomedical engineering, flexible sensors have achieved rapid development and widespread application. In particular, HBS, as key components of intelligent bioelectronic devices and human-machine interaction systems [1-4], have made significant breakthroughs in recent years. Hydrogels are three-dimensional network polymer materials formed by cross-linked hydrophilic polymers, capable of absorbing large amounts of water while maintaining a solid form. They possess excellent mechanical properties, flexibility, conductivity, strain sensitivity, and biocompatibility. Their three-dimensional hydrophilic network structure enables direct and close contact with human tissues, accurately capturing subtle physiological signals (e.g., pulse, respiration) as well as large-scale limb movements (e.g., joint bending). As a result, HBS have been widely used in human motion detection and health monitoring [5].

Based on their working mechanisms, HBS can be classified into four categories: resistive, capacitive, piezoelectric, and triboelectric [6]. Resistive and capacitive HBS are active sensors, while piezoelectric and triboelectric HBS are passive sensors. In recent years, most researchers have focused on material design and structural optimization, successfully enhancing the performance of HBS. However, HBS still face three core challenges: First, it is difficult to balance mechanical properties and conductivity, as high stretchability often leads to reduced conductivity or sensitivity [7]. Second, as hydrogels are prone to swelling in aqueous environments, leading to performance

degradation [8]. Third, achieving multimodal sensing remains challenging, as synchronously detecting strain, temperature, and biochemical signals in a single device is still a difficulty [9]. To address these issues, researchers have introduced conductive fillers (e.g., PPy, PANI, MXene, carbon nanotubes) [10], constructed multi-layer network structures [11], and regulated electron and ion migration behaviors or formed conductive pathways within hydrogels. These efforts have successfully developed hydrogel materials with high stretchability (>2840%) [12], a wide strain response range (0-900%) [13], and high sensitivity (GF >15.56) [14]. For example, Wu et al. [15] developed a polyacrylamide/carboxymethyl cellulose double-network hydrogel (PCM) sensor by incorporating MXene conductive fillers. The formation of tight hydrogen bonds between hydroxyl groups (-OH) and PAM/CMC chains enhanced the mechanical properties of the hydrogel, while conductive pathways were constructed within the system, significantly improving both the mechanical and conductive properties of the HBS.

In terms of structural optimization, researchers have designed specific micro- and macrostructures to enhance the comprehensive performance and multimodal sensing capabilities of HBS. These include double-network structures (DN), microstructures such as porous, honeycomb, and columnar designs, interpenetrating polymer network structures, core-shell structures, and hierarchical structures. These innovations have enabled multifunctional integration and performance optimization. For instance, Zhang et al. [16] designed a self-powered double-network piezoelectric hydrogel with 3D interconnected cellulose and poly(vinylidene fluoride-trifluoroethylene) (C/P(VDF/TrFE)) microstructures, improving the flexibility of the HBS while maintaining its mechanical and conductive properties.

In light of this, this review systematically summarizes the latest progress of HBS in human motion detection and health monitoring. Chapter 2 elaborates on the multimodal sensing responsiveness of HBS in human motion detection and health monitoring, clarifying the sensing mechanisms of resistive, capacitive, piezoelectric, and triboelectric HBS. Chapter 3 introduces the applications of HBS-based medical monitoring systems in wearable physiological signal detection. Chapter 4 focuses on the applications of HBS-based medical monitoring systems in implantable physiological signal monitoring. Chapter 5 provides a summary and outlook. It is hoped that this review will serve as a reference for the future design and innovation of HBS in human motion detection and health monitoring, thereby promoting their application in the interdisciplinary field of flexible electronics and biomedical engineering.

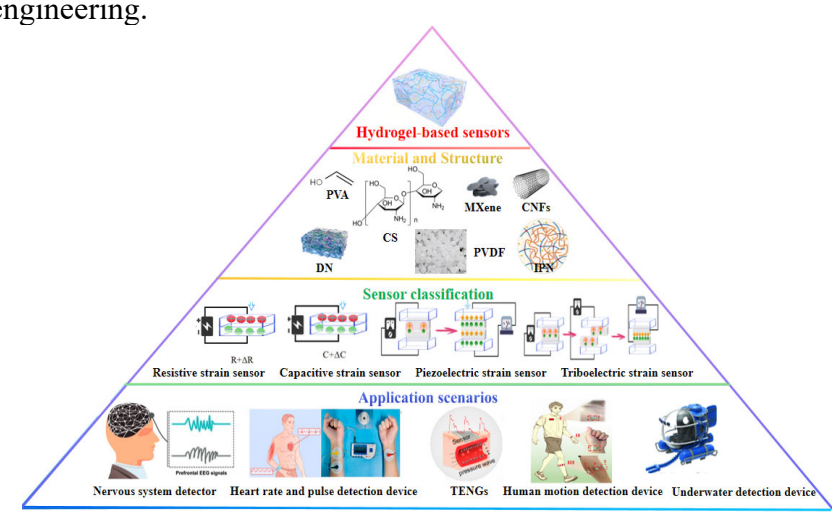

Figure 1 Material structure design and functional applications of HBS, chemical formulas and schematic diagrams [10][17][15]; EEG monitoring [18]; heart rate and pulse [19]; TENGs [20]; human motion detection [20]; deep-sea exploration [21]

2. Multimodal Sensing Responsiveness of HBS

2.1 Classification of HBS

Based on these mechanisms, HBS can be divided into four types: piezoresistive sensors, capacitive sensors, piezoelectric sensors, and triboelectric sensors.

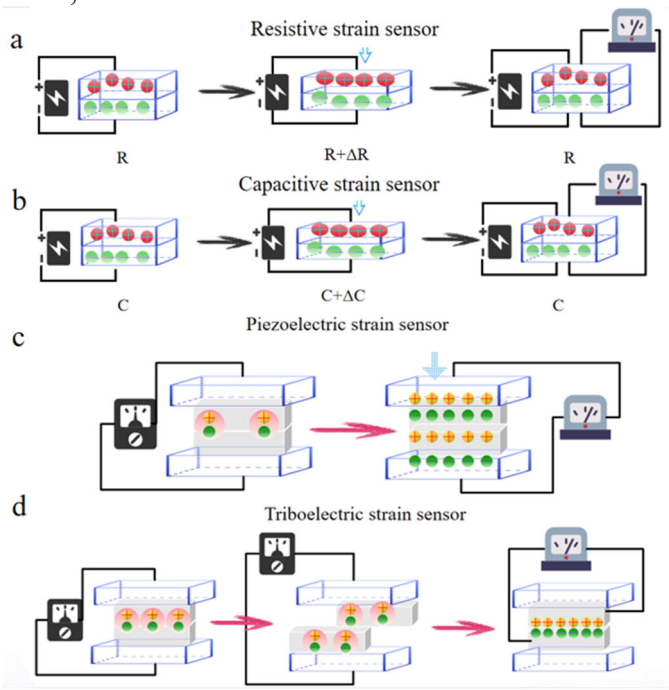

Figure 2 (a-d) Diverse sensing mechanisms of HBS: (a) resistive, (b) capacitive, (c) piezoelectric, (d) triboelectric

2.2 Working Principles of HBS

For resistive HBS materials, deformation causes corresponding changes in length and cross-sectional area. According to the resistance formula:

$$R=\rho\frac{l}{S}\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(1)$$

(where ρ is resistivity, l is length, and S is cross-sectional area), changes in the length and cross-sectional area of the hydrogel lead to variations in its resistance. When the deformation is released, the resistance of the hydrogel material returns to its original state, thereby converting material deformation into an electrical signal for output. Resistive HBS offer advantages such as simple structure, ease of fabrication, sensitivity to strain signals, and the ability to detect various mechanical signals. However, these sensors also have some drawbacks: their detection performance is susceptible to environmental factors

The sensing mechanism of capacitive HBS is similar to that of resistive HBS, with the difference being that capacitive HBS operate based on changes in capacitance caused by deformation of the compressible dielectric. According to the capacitance formula:

$$C=\frac{\varepsilon S}{d}\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(2)$$

(where ε is the dielectric constant, S is the cross-sectional area, and d is the electrode spacing), the sensing function is achieved. Capacitive HBS offer advantages such as high sensitivity, ability to detect minute deformations, strong anti-interference capability, fast response speed, and suitability for dynamic signal detection. However, they also have limitations, including a relatively limited measurement range, risk of electrode short-circuiting under large deformations and susceptibility to environmental influences, which can affect measurement accuracy.

Due to their unique sensing mechanisms and significant performance advantages, resistive and capacitive HBS demonstrate broad application prospects in human motion detection and health

monitoring. However, for implantable HBS such as cardiac pacemakers that require self-powering, resistive and capacitive HBS cannot meet the requirements, as they typically rely on external power from batteries. This not only increases the cost of frequent battery replacement but also fails to meet the practical needs of patients.

To address energy issues and reduce the hassle of frequent battery replacement, various self-powered HBS (e.g., piezoelectric, triboelectric, electrochemical) have been developed in recent years. Piezoelectric and triboelectric HBS, as self-powered passive HBS, achieve mechanoelectrical coupling through self-powering effects. Piezoelectric HBS utilize the piezoelectric effect for self-powering, where mechanical stress induces electrode polarization (surface charge separation) through the synergy of non-centrosymmetric charge distribution and directional ion migration. The piezoelectric effect can be enhanced by introducing piezoelectric fillers (e.g., PVDF nanofibers), forming topological structures, or injecting high-mobility ions (H^+, Zn^{2+}). The advantages of piezoelectric HBS include self-powering, suitability for long-term monitoring, sensitivity to dynamic pressure/vibration, and fast response speed. However, they are insensitive to static pressure, produce weak output signals (requiring high-gain amplification circuits), and demand high compatibility between piezoelectric materials and hydrogels, along with complex fabrication processes.

Triboelectric HBS achieve self-powering through the triboelectric effect. Specifically, when two different materials come into contact, charge transfers from the material with higher electron affinity to the one with lower electron affinity, completing the self-powering process of triboelectric HBS. These sensors offer several advantages: high sensitivity, ability to detect subtle human motions, self-powering capability, low fabrication cost, and a wide range of material choices. However, they also have some disadvantages: charge is prone to decay, susceptibility to external environmental influences, poor signal stability, often require combination with other materials, and relatively complex structures. Additionally, triboelectric HBS can be applied in the fabrication of triboelectric nanogenerators (TENGs) [22], offering unique advantages in sensing applications, such as human motion, biomechanics, and human-machine interfaces.

3. Applications of HBS in Wearable Physiological Signal Detection

HBS can be categorized into active and passive types based on their energy supply methods, each with distinct application fields and prospects.

3.1 Active Hydrogels

Active HBS (e.g., resistive and capacitive types) rely on external power sources for continuous energy input and achieve signal conversion by monitoring changes in resistance or capacitance. This operational mode offers advantages such as signal stability and high measurement accuracy, making them particularly suitable for medical diagnostics and human-machine interaction scenarios requiring continuous monitoring.

3.1.1 Resistive HBS

Hydrogels are prone to swelling in aqueous environments and suffer from performance degradation at low temperatures due to ion channel blockage and water freezing, which severely limits their application scope. To address these issues, Zhang et al. [23] proposed a composite hydrogel preparation strategy based on a novel deep eutectic solvent (DES). This DES, composed of 1-butyl-3-methylimidazolium (BMIMCI) and acetone ketal, exhibits both conductivity and antifreeze properties. Using acrylic acid (AA), [2-(methacryloyloxy)ethyl] dimethyl (3-sulfopropyl) ammonium hydroxide (SBMA), and dodecyl acrylate (DA) as monomers, a physically cross-linked PSA-DA/DES composite hydrogel was synthesized via one-step photopolymerization in a DES/H_2O binary solvent. This hydrogel demonstrates high transparency, stretchability (strain response range: 0-500%), anti-swelling properties, adhesiveness, self-healing capability, and antifreeze performance, with a strain sensing gauge factor (GF) of 3.9. It is suitable for human motion monitoring (e.g., fingers,

wrists, elbows) as well as applications in underwater communication and marine exploration. Wang et al. [24] utilized the synergistic effects of polyvinyl alcohol (PVA), chitosan (CS), 4-carboxyphenylboronic acid (PBA), glycerol (GL), and MXene to prepare an antifreeze and water-retaining hydrogel via a one-pot method and cyclic freeze-thaw process. The strain response range of this hydrogel is 0-600%, with a maximum GF of 7.03 in the 300-600% strain range. Owing to its outstanding mechanical properties, conductivity, frost resistance, and water retention, this hydrogel shows broad application potential in artificial intelligence, speech rehabilitation training, and communication for the deaf and mute.

Integrating underwater adhesion and self-healing properties into a single HBS remains a significant challenge. To address this, Ling et al. [14] used dialdehyde carboxymethyl cellulose (DCMC), chitosan (CS), polyacrylic acid (PAA), and aluminum ions to successfully construct a multifunctional polysaccharide double-network DCP (DCMC/CS/PAA) HBS with high stretchability and sensitivity. The first network is formed via Schiff base covalent bonds between CS and DCMC, while the second network is constructed through metal coordination between PAA chains and Al^{3+} ions. This composite hydrogel exhibits a broad strain response range (3-800%), with a sensitivity of up to 15.56 in the low-strain range (110-320%). It demonstrates a self-healing rate >90%, self-healing time <10 minutes, and an underwater adhesion strength of 32 kPa on pigskin, enabling sensitive monitoring of human motion underwater.

Wang et al. [13] employed polyvinyl alcohol (PVA) and poly(acrylamide-co-2-acrylamido-2-methylpropanesulfonic acid) P(AM/AMPS) to construct an interpenetrating polymer network (IPN) fluorescent hydrogel, PVA-P(AM/AMPS)--Gly-Ln^{3+}, via a chemically cross-linked network. The strain sensing range of this hydrogel reaches 0-900%, with a sensitivity of 5.3 in the 300-900% strain range and an adhesion strength of 12.9 kPa on pigskin. Under 365 nm ultraviolet excitation, Eu^{3+} hydrogel and Tb^{3+} hydrogel emit red and green fluorescence at emission spectrum bands centered at 615 nm and 544 nm, respectively. With excellent mechanical properties, adhesiveness, conductivity, and photoluminescence characteristics, this hydrogel holds broad application prospects in human motion detection and information encryption.

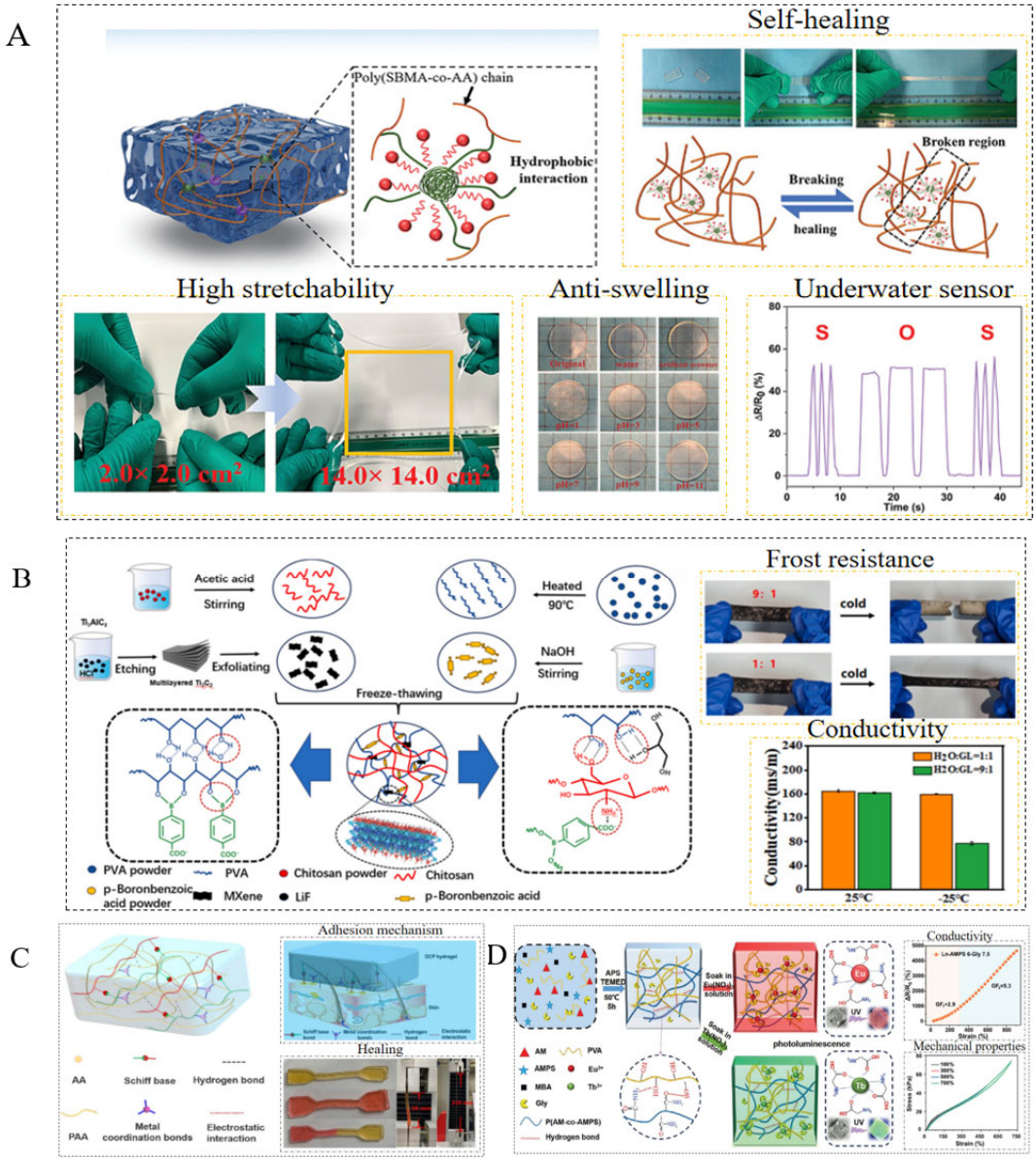

Figure 3.1 (A-E) Structure and properties of resistive HBS [23][24][14][13]: (A) Physically cross-linked hydrogel and its properties [23]; (B) Antifreeze and water-retaining hydrogel and its frost resistance [24]; (C) Double-network hydrogel and its self-healing and adhesive properties [14]; (D) Fluorescent hydrogel and its electromechanical properties [13].

3.1.2 Capacitive HBS

To address the common limitations of wearable sensors such as low sensitivity, opacity, and poor self-healing performance, Jing's team [11] successfully developed a polyvinyl alcohol/cellulose carbon nanofiber (PVA/CNF D) hydrogel based on a dual-crosslinked network. Compared to pure PVA hydrogel, this novel hydrogel exhibits rapid self-healing capability, exceptional electromechanical properties, high sensitivity, high transparency, and good biocompatibility. It is widely applicable for detecting subtle pressure and human motion. Yin's team [25] prepared a gelatin-based hydrogel enhanced by incorporating reduced graphene oxide (rGO) to form abundant non-covalent interactions and a composite conductive network, thereby improving its electromechanical performance. This hydrogel achieves a fracture stress of 1694.2 kPa and a fracture toughness of 701.1 kJ/m^3. Its strain detection range is 0–35%, with a sensitivity as high as 8.2 within the 20–25% strain range. Consequently, this hydrogel can effectively detect human motion and is suitable for multifunctional flexible electronic devices. Yang's team [26] employed a solvent replacement method to fabricate a

hydroxyethyl methacrylate-ethylene glycol (HEMA-EG) hydrogel with a polymer network structure. Hydrogen bonds and hydrophobic interactions endow it with anti-swelling properties, outstanding mechanical performance, conductivity, and self-healing capability. The hydrogel demonstrates a fracture stress of 149.25 kPa and an elongation at break of 523%. Within the strain response range of 0–200%, its sensitivity reaches 0.678. This sensor can not only monitor underwater human motion but also detect water quality and temperature to ensure the health and safety of underwater workers. Ren's team [27] added 2-(methacryloyloxy)ethyl butyldimethyl-(3-sulfopropyl)ammonium hydroxide (SBMA) and hydroxyethyl methacrylate (HEMA) to PVA to prepare a hydrogel via cyclic freeze-thaw method. Through electrostatic repulsion of polyzwitterions, hydrogen bonds, and hydrophobic interactions, the hydrogel exhibits excellent anti-swelling properties. Additionally, it possesses remarkable mechanical and strain sensing performance. After one day of underwater immersion, its strain response range remains 0–300%, with a sensitivity as high as 3.356 particularly in the 200–300% strain range. Therefore, this hydrogel holds broad application prospects in the field of underwater motion detection.

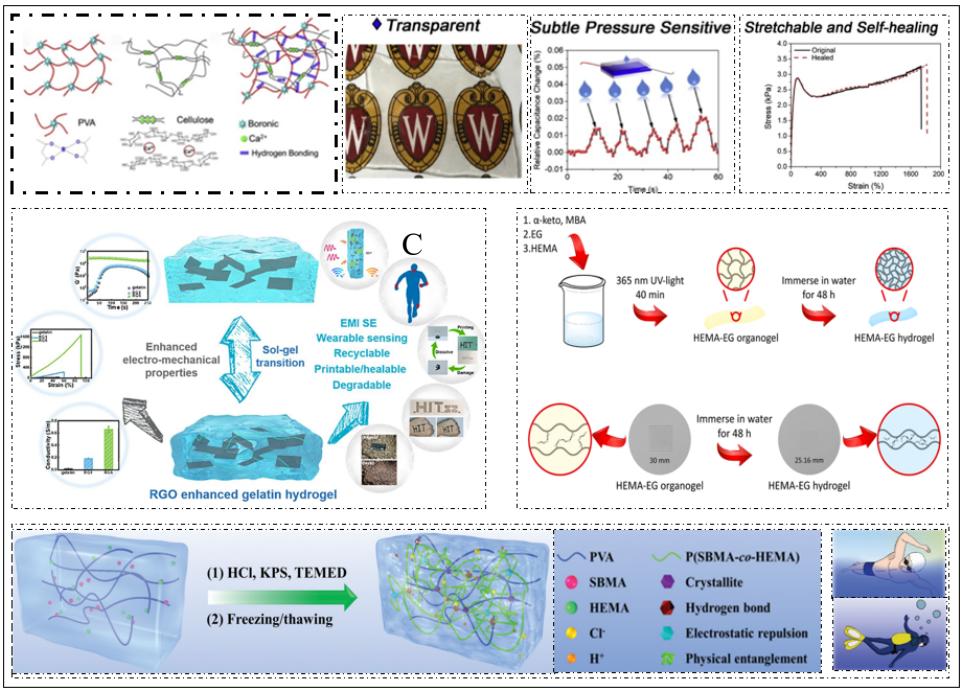

Figure 3.2 (A-D) Structure, properties, and applications of capacitive hydrogels [11][25][26][27]. (A) Structure of (PVA/CNF D) hydrogel, along with its transparency, sensitivity to subtle pressure detection, high stretchability, and self-healing properties [11]; (B) Structure, properties, and applications of gelatin hydrogel [25]; (C) Preparation of (HEMA-EG) hydrogel [26]; (D) Structure of anti-swelling hydrogel and its underwater applications [27].

4. Applications of HBS in Implantable Physiological Signal Monitoring

Passive HBS (e.g., piezoelectric and triboelectric types) can directly convert mechanical energy into electrical signals through piezoelectric or triboelectric effects, achieving true self-powering capabilities. This energy conversion mechanism endows them with unique advantages in the field of implantable physiological signal monitoring.

Currently, simultaneously achieving self-powering, high sensitivity, high strength, and flexibility in piezoelectric hydrogels remains challenging. To address this, Zhang et al. [16] prepared a self-powered double-network piezoelectric hydrogel with 3D interconnected cellulose and poly (vinylidene fluoride-trifluoroethylene) (C/P (VDF/TrFE)) microstructures using a co-solvent method. The double-network structure of flexible cellulose and rigid P (VDF-TrFE) achieves a balance between high strength and high flexibility. This hydrogel exhibits a pressure response range of 0.5–

50 kPa, with a sensitivity of 13.4 $mV \cdot kPa^{-1}$ in the 0.5–20 kPa range, a flexural strength of 5.17 MPa, and a fracture toughness of 2.61 MJ/m^3, which can be used for energy harvesting in cardiac pacemakers and the development of self-powered wearable human-machine interfaces (HMI).

Sun et al. [28] investigated the influence of crosslinker content on the electromechanical properties of hydrogels by studying deformation recovery and ion migration. The results indicated that highly crosslinked hydrogels narrow the channels for ion migration through the polymer network, thereby reducing the overall ion migration rate. However, due to the higher modulus of the material, highly crosslinked hydrogels recover more quickly after stress release. This suggests that higher crosslinking degrees lead to slower ion migration but faster deformation recovery, while low-crosslinked hydrogels exhibit the opposite characteristics. Thus, by adjusting the crosslinking degree of the hydrogel, its conductive properties can be modulated. Wearable devices for facial expression recognition (FER) face challenges in achieving accurate and convenient identification. To address this, Zhao et al. [29] prepared a triboelectric hydrogel using 3-[dimethyl-[2-(2-methylprop-2-enoyloxy)ethyl]azaniumyl]propane-1-sulfonate (DMAPs), acrylamide (AM), and LiCl as raw materials. It possesses excellent mechanical and conductive properties. Additionally, by attaching four triboelectric HBS near the forehead, cheeks, eyes, and mouth, respectively, a facial sensor network was constructed to collect expression signals. Using a deep learning-based one-dimensional convolutional neural network, the system can accurately recognize facial expressions.

Currently, cellulose-based hydrogels have long self-healing times, making it difficult to meet the application requirements of wearable sweat TENGs sensors. Qin et al. [30] proposed a dynamically crosslinked hydrogel composed of polyaniline (PANI), in-situ polymerized 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO)-oxidized nanocellulose (TOCNF), and PVA/borax (PVAB). The abundant hydrogen bonds in its reversible dynamic network, along with the conjugated π-electron system formed by the benzene and quinone rings in PANI, endow the hydrogel with excellent mechanical properties, rapid self-healing ability, and outstanding conductivity. The CPPH hydrogel was assembled with a highly selective hydrophobic ion-selective membrane (ISM) and encapsulated with PDMS to prepare a self-powered sweat sensor. This sensor enables real-time sweat detection and holds broad application prospects in the field of human health monitoring. To address issues such as high energy consumption, poor mechanical properties, and inadequate environmental adaptability in current hydrogels, Yuan et al. [12] successfully prepared a triboelectric hydrogel. This hydrogel exhibits exceptional stretchability, frost resistance, drying resistance, conductivity, and adhesiveness. Utilizing a lignin-based macromolecular self-catalytic system (SL-Fe^{3+}) to provide energy, rapid in-situ polymerization of monomers was initiated to generate poly(ammonium acrylate) (PAM) chains. Subsequently, trehalose (Tr) was added to form strong hydrogen bond interactions with the PAM chains. These strong hydrogen bonds confer high stretchability (2840%), excellent frost resistance (-18°C), and drying resistance (40°C) to the hydrogel, along with good conductivity and adhesiveness. This hydrogel can be used to manufacture wearable electronic devices for detecting finger bending movements and can also be integrated with smart mechanical grippers to enable the grasping of various objects. Therefore, it holds broad application prospects in unmanned factories, virtual supermarkets, and other fields in the smart era.

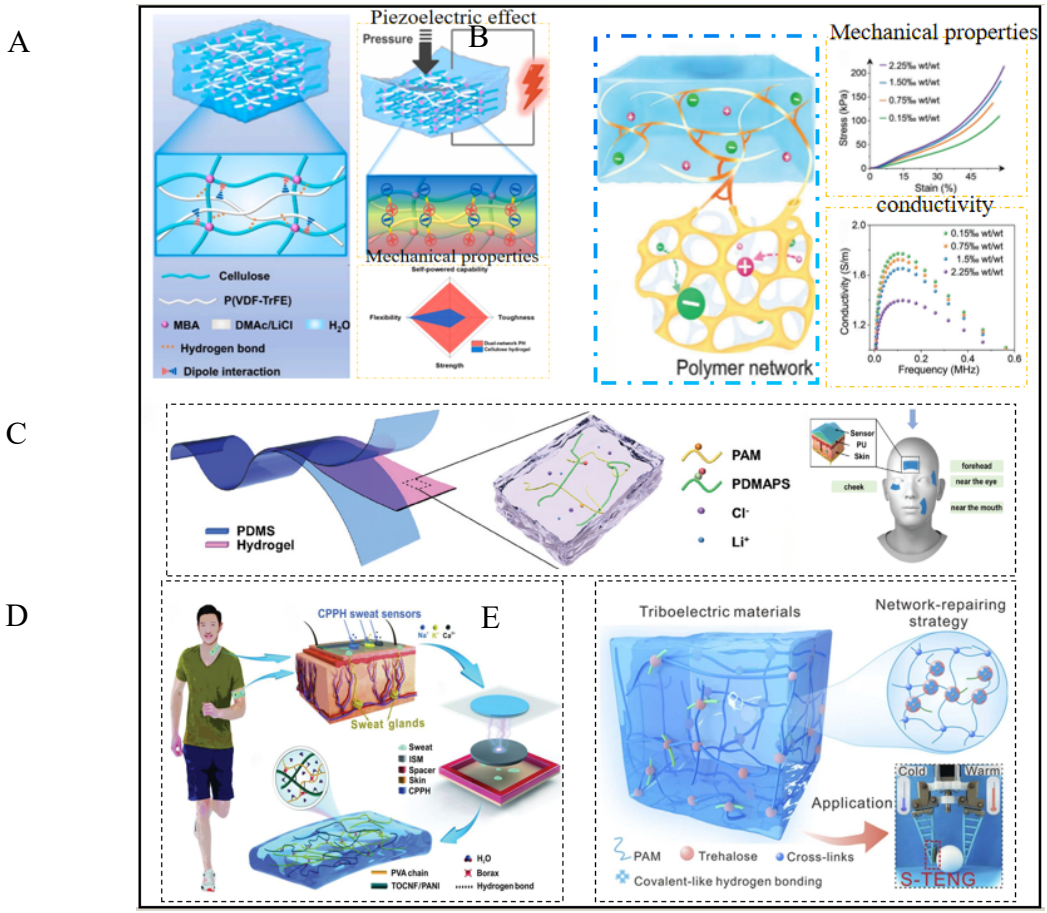

Figure 4 (A-E) Structure and applications of piezoelectric and triboelectric hydrogels [16][28][29][30][12]: (A) Piezoelectric effect and mechanical properties of piezoelectric hydrogel [16]; (B) Structure of piezoelectric hydrogel and the influence of crosslinking degree on electromechanical properties [28]; (C-E) Structure and applications of triboelectric hydrogels [29][30][12].

5. Conclusion and Prospect

As a key device at the intersection of flexible electronic technology and biomedical engineering, HBS has achieved significant breakthroughs in recent years in material design, structural optimization, performance regulation, and application expansion. First, this review summarizes the sensing mechanisms of resistive, capacitive, piezoelectric, and triboelectric HBS. Second, in terms of material and structural design, this paper outlines strategies for optimizing the performance and applications of HBS. Subsequently, it summarizes the applications of HBS in human motion detection and health monitoring, covering wearable biophysiological signal monitoring systems and implantable biomedical systems. In the future, the development of HBS will rely on the synergistic advancement of materials science, engineering technology, and interdisciplinary research. By overcoming performance bottlenecks and application limitations, HBS is expected to become a core technology driving innovations in health monitoring, human-machine interaction, and flexible electronics.

References

[1] Zhang, Y. (2025). "Wearable Sensors: An ACS Sensors Special Issue." ACS Sensors 10(5): 3189-3191.

[2] Fang, K., et al. (2023). "Hydrogel-Based Sensors for Human-Machine Interaction." Langmuir 39(48): 16975-16985.

[3] Wang, H., et al. (2024). "High-Performance Hydrogel Sensors Enabled Multimodal and Accurate Human-Machine Interaction System for Active Rehabilitation." Advanced Materials 36(11): 2309868.

[4] Zhou, B. and W. Yuan (2024). "Tunable thermoresponsive and stretchable hydrogel sensor based on hydroxypropyl cellulose for human motion/health detection, visual signal transmission and information encryption." Carbohydrate Polymers 343: 122497.

[5] Cheng, B., et al. (2021). "An adhesive and self-healable hydrogel with high stretchability and compressibility for human motion detection." Composites Science and Technology 213: 108948.

[6] Fan, Z., et al. (2023). "Recent Progress in Mechanically Robust and Conductive-Hydrogel-Based Sensors." Advanced Intelligent Systems 5(10): 2300194.

[7] Shu, K., et al. (2024). "A synergistic enhancement strategy for mechanical and conductive properties of hydrogels with dual ionically cross-linked κ-carrageenan/poly(sodium acrylate-co-acrylamide) network." Carbohydrate Polymers 346: 122638.

[8] Boran, F. (2021). "The influence of freeze-thawing conditions on swelling and long-term stability properties of poly(vinyl alcohol) hydrogels for controlled drug release." Polymer Bulletin 78(12): 7369-7387.

[9] Liu,H.,etal.(2025)."Multimodal soft sensor integrated with hydrogel-optoelectronic for wrist motion monitoring." Measurement 239: 115486.

[10] Han, F., et al. (2021) Materials, Electrical Performance, Mechanisms, Applications, and Manufacturing Approaches for Flexible Strain Sensors. Nanomaterials 11, DOI: 10.3390/nano11051220

[11] Jing, X., et al. (2019). "Highly transparent, stretchable, and rapid self-healing polyvinyl alcohol/cellulose nanofibril hydrogel sensors for sensitive pressure sensing and human motion detection." Sensors and Actuators B: Chemical 295: 159-167.

[12] Yuan, J., et al. (2024). "Anti-freeze, anti-dehydrating and stretchable triboelectric materials enabled by covalent-like hydrogen bond interaction." Nano Energy 131: 110215.

[13] Wang, F., et al. (2025). "Lanthanide-Coordinated Multifunctional Hydrogel for Detecting Human Motion and Encrypting Information." Advanced Functional Materials 35(24): 2418373.

[14] Ling, Q., et al. (2022). "Highly Sensitive and Robust Polysaccharide-Based Composite Hydrogel Sensor Integrated with Underwater Repeatable Self-Adhesion and Rapid Self-Healing for Human Motion Detection." ACS Applied Materials & Interfaces 14(21): 24741-24754.

[15] Wu, W., et al. (2024). "Highly sensitive MXene-enhanced polyacrylamide/ carboxymethyl cellulose double-network hydrogels with wide operation range for wearable electronics." Industrial Crops and Products 214: 118573.

[16] Zhang, C., et al. (2025). "Nature-inspired helical piezoelectric hydrogels for energy harvesting and self-powered human-machine interfaces." Nano Energy 136

[17] Chen, J., et al. (2024). "An overview of conductive composite hydrogels for flexible electronic devices." Advanced Composites and Hybrid Materials 7(2): 35.

[18] Chen, B., et al. (2025). "Recent Progress of Biomaterial-Based Hydrogels for Wearable and Implantable Bioelectronics." Gels 11(6): 442.

[19] He, S., et al. (2024). "Fabrication of anti-freezing and self-healing hydrogel sensors based on carboxymethyl guar gum and poly(ionic liquid)." International Journal of Biological Macromolecules 279: 135112.

[20] Song, Z., et al. (2023) Flexible and Wearable Biosensors for Monitoring Health Conditions. Biosensors 13, DOI: 10.3390/bios13060630

[21] Liu, S., et al. (2023). "Tactile Sensing for Soft Robotic Manipulators in 50 MPa Hydrostatic Pressure Environments." Advanced Intelligent Systems 5(12): 2300296.

[22] Qin, Y., et al. (2023). "Cellulosic gel-based triboelectric nanogenerators for energy harvesting and emerging applications." Nano Energy 106: 108079.

[23] Zhang, Z., et al. (2024). "Transparent, Highly Stretchable, Self-Healing, Adhesive, Freezing-Tolerant, and Swelling-Resistant Multifunctional Hydrogels for Underwater Motion Detection and Information Transmission." Advanced Functional Materials 34(49).

[24] Wang, T., et al. (2025). "PVA/chitosan-based multifunctional hydrogels constructed through multi-bonding synergies and their application in flexible sensors." Carbohydrate Polymers 350.

[25] Yin, R., et al. (2023). "Transient, printable and recyclable gelatin hydrogels with enhanced mechanical sensing and electromagnetic shielding performance by incorporation of reduced graphene oxide." Chemical Engineering Journal 475

[26] Yang, Y., et al. (2023). "Easy-to-Prepare Flexible Multifunctional Sensors Assembled with Anti-Swelling Hydrogels." ACS Applied Materials & Interfaces 15(39): 46417-46427.

[27] Ren, J., et al. (2021). "An Anti-Swellable Hydrogel Strain Sensor for Underwater Motion Detection." Advanced Functional Materials 32(13).

[28] Sun, Y., et al. (2024). "Crosslinking-Modulated Hydrogel Piezoionic Senor for Pattern Security Authentication in Human-Machine Interfaces." Advanced Functional Materials 35(19).

[29] Zhao, Y., et al. (2024). "A High-Accuracy Facial Expression Recognition System Combining Triboelectric Hydrogel Sensors With Deep Learning." Advanced Functional Materials 35(19).

[30] Qin, Y., et al. (2022). "Stretchable Triboelectric Self-Powered Sweat Sensor Fabricated from Self-Healing Nanocellulose Hydrogels." Advanced Functional Materials 32(27).