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REVIEW

Poly(3,4-ethylenedioxythiophene):Poly(styrenesulfonate)-Based Hydrogel Strain Sensors: Materials, Fabrication, Performance, and Applications

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ABSTRACT: Hydrogel strain sensors are widely used in wearable electronics, human-machine interfaces, flexible electronics, owing to their ability to convert mechanical deformation into electrical signals. This function requires sensor materials to possess both high compliance and electrical conductivity. Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) has emerged as an ideal candidate for hydrogel strain sensors due to its soft and flexible mechanical properties, tunable mechanical performance, mixed ionic-electronic conductivity, and excellent processability. Although extensive research has been conducted on PEDOT:PSS-based hydrogel strain sensors, there is currently no systematic review that elucidates the translation pathway from high-performance materials design and advanced fabrication processes to diverse application scenarios. This review systematically examines the current state of development of PEDOT:PSS-based hydrogel strain sensors, following a logical progression from material design and fabrication processes to performance optimization and applications. It is expected to accelerate the development of PEDOT:PSS-based hydrogel strain sensors and expand their application space into a wider variety of fields.

KEYWORDS: Conducting polymer hydrogels; PEDOT:PSS; strain sensors; flexible electronics; wearable devices

1 Introduction

Hydrogel strain sensors, as key devices for converting mechanical deformation into electrical signals, hold significant application value in cutting-edge fields such as bioelectronics [1,2], flexible sensing [3,4], and soft robotics [5,6]. To achieve high sensitivity, a broad response range, and feasible stability in sensing performance, their core materials must simultaneously possess excellent flexibility, stretchability, and controllable conductivity [7–11]. Conducting polymer hydrogels, by incorporating functional conductive components into the hydrogel network, successfully integrate the biomimetic mechanical properties of biological tissues with tunable electrical characteristics, making them an ideal material system for constructing a new generation of high-performance flexible hydrogel strain sensors [12–14]. Among the various conducting polymer hydrogels, poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT:PSS) has emerged as one of the most extensively researched material in this field due to its high conductivity [15,16], tunable physicochemical properties [17,18], and well-established processing foundation [19,20]. Compared with conventional conductive materials (such as carbon-based materials and metal nanoparticles), PEDOT:PSS exhibits unique advantages in constructing hydrogel strain sensors. Carbon-based materials suffer from poor dispersion and unsatisfactory interfacial compatibility; metal nanoparticles are prone to oxidation and raise concerns regarding cytotoxicity. In contrast, PEDOT:PSS, as an intrinsically conductive polymer, combines excellent solution processability [21,22], favorable mechanical compatibility [23], and outstanding biocompatibility, making it particularly suitable for constructing strain sensors with complex structures and integrated functionalities [24–26]. Since 2015, research on PEDOT:PSS hydrogels has shown a rapid growth trend. Notably, in 2025, the annual publication volume of research related to PEDOT:PSS hydrogel strain sensors doubled, accounting for approximately one-third of the total literature on this material system. This highlights the sustained attention and focused investment from both academia and industry in this direction (Fig. 1a).

To more clearly reveal the technological drivers behind this rapid growth trend, Fig. 1b further outlines the key milestone works in the development trajectory of this field. The evolution of research over the past decade can be summarized into the following three aspects. Material design has remained the core of sensor research throughout the entire decade. From intrinsic property optimization and composite system construction to multi-property synergistic design, materials have always been the foundation of sensor research, with all performance breakthroughs built upon a deep understanding and rational design of the material system. Beyond materials, sensor performance enhancement and fabrication processes are equally critical. Researchers have developed structural design strategies such as microcracks, salting-out, and double-network structures to improve various performance metrics, while advancing fabrication processes from laboratory-scale casting toward advanced manufacturing techniques such as 3D printing and laser-induced processing. Building upon these foundations, the field is progressively moving toward practical applications. Application scenarios have expanded from human motion monitoring to cutting-edge fields such as soft robotics and plant growth monitoring, progressively advancing toward intelligent perception and system integration, demonstrating significant potential for transitioning from laboratory research to practical applications. These driving studies have achieved a series of important advances in material design, performance breakthroughs, integration technologies, and advanced manufacturing, collectively shaping the evolutionary path of this field from fundamental research toward application exploration (Fig. 1b).

With the deepening of research, a variety of structural design strategies and fabrication processes have emerged [27–29]. However, the field currently still lacks a systematic and in-depth exploration and theoretical synthesis of the interconnections between "material design-fabrication process-performance outcomes-practical applications" which constrains the scientific development and systematic breakthroughs in this technological direction. Therefore, comprehensively reviewing the developmental trajectory of this field and constructing a cognitive framework that spans the entire workflow holds significant academic value and practical importance for advancing the field from empirical exploration toward rational design.

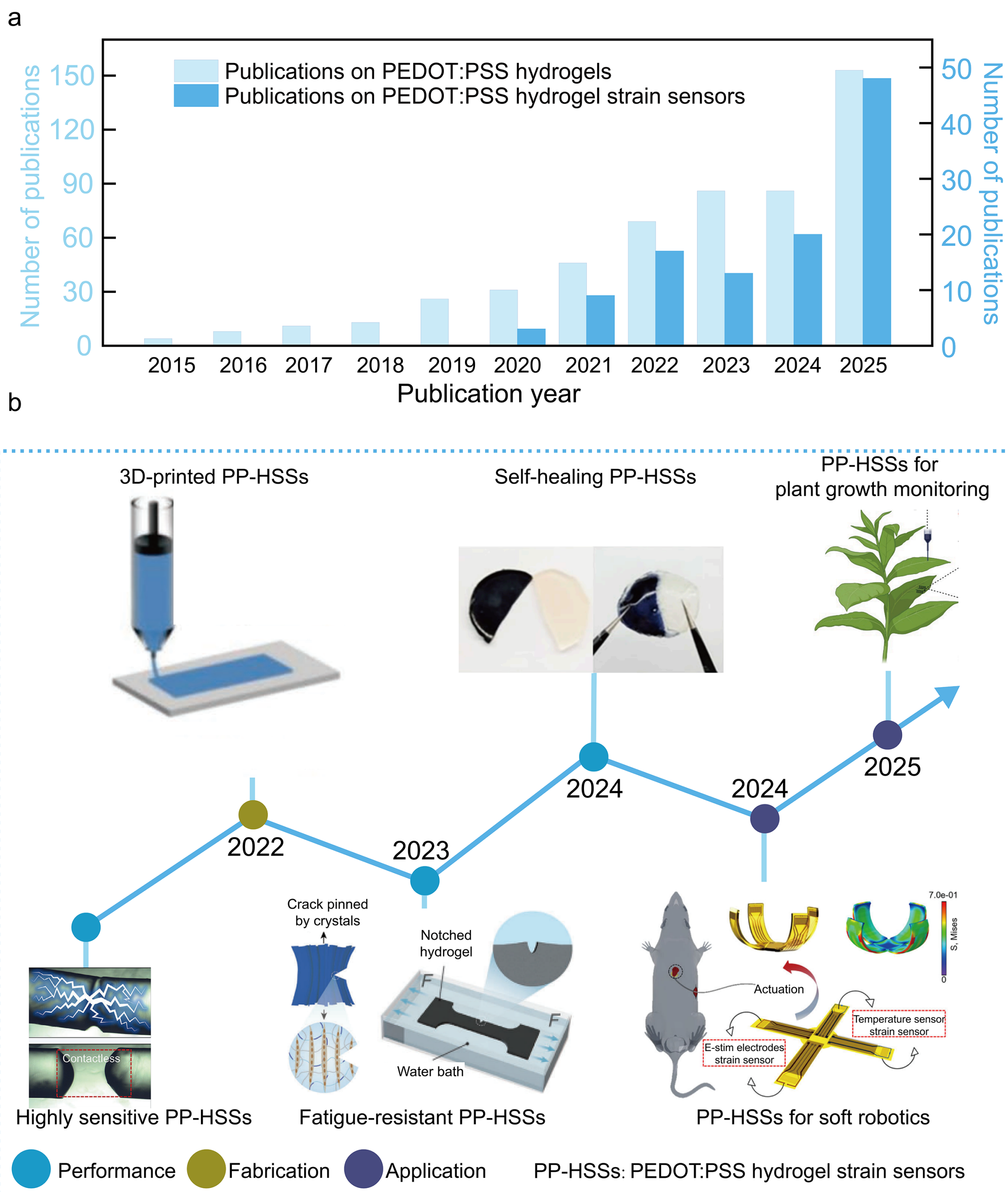


Figure 1: The research dynamics and development history of the PEDOT:PSS hydrogel and its strain sensor field from 2015 to 2025. (**a**) Publication counts and trends for research on "PEDOT:PSS hydrogels and PEDOT:PSS hydrogel strain sensors" from 2015 to 2025, based on a web of science search (25 January 2026). (**b**) Timeline highlighting selected developments in PEDOT:PSS hydrogel strain sensors over the past decade. Reprinted/adapted with permission from reference [30]. Copyright 2025, copyright Wiley; [31]. Copyright 2022, copyright Wiley; [32]. Copyright 2023, copyright Wiley; [33]. Copyright 2025, copyright ACS Publications; [34]. Copyright 2024, copyright Nature; [35]. Copyright 2025, copyright ACS publications.

The structure of this review is as follows: Section 2 systematically elaborates on the material systems and composition design principles of PEDOT:PSS hydrogel strain sensors. Section 3 focuses on their fabrication techniques, covering forming methods from fibers and films to three-dimensional structures. Section 4 delves into the latest advancements in such materials regarding mechanical property enhancement, self-healing characteristics, sensitivity improvement, and response hysteresis regulation. Section 5 comprehensively reviews their current application status and representative examples in cutting-edge fields such as human motion monitoring, soft robotics, human-computer interaction, and plant physiological monitoring. Finally, the review concludes by summarizing the key challenges currently faced and providing an outlook on future development trends. This paper aims to systematically clarify the intrinsic relationships among "material-fabrication-performance-application" for PEDOT:PSS hydrogel strain sensors, offering a theoretical foundation and technical guidance for subsequent research in the field. The overall structure of the paper is illustrated in Fig. 2.

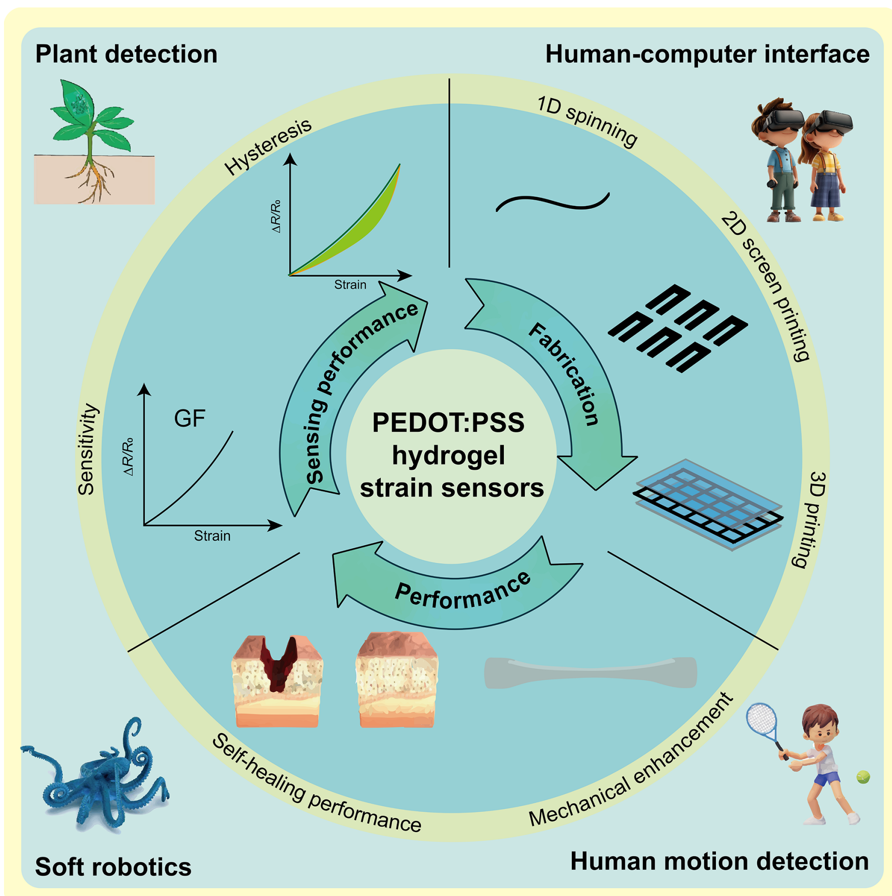


Figure 2: The schematic illustrates the outline of this review, covering the materials, fabrication, performance, and applications of PEDOT:PSS-based hydrogel strain sensors.

2 Material Composition and Design of PEDOT:PSS Hydrogel Strain Sensors

In the performance composition of PEDOT:PSS hydrogel strain sensors, the intrinsic properties of each constituent material collectively lay the foundation for their core functionality. Compared to other materials, PEDOT:PSS possesses unique advantages. In terms of sensing performance, PEDOT:PSS hydrogel strain sensors typically exhibit a wider working range and higher sensitivity compared to strain sensors based on other materials (Table 1). Regarding other properties, PEDOT:PSS demonstrates excellent processability and environmental stability, making it particularly suitable for aqueous solution processing and flexible electronics. When compared with carbon-based materials such as graphene and carbon nanotubes, PEDOT:PSS shows a certain gap in electrical conductivity; nevertheless, its excellent film-forming ability and biointerface compatibility grant it a unique advantage in the field of bioelectronics. Relative to metal-based materials such as gold and silver nanowires, PEDOT:PSS stands out in terms of flexibility and low-cost solution processing, although its electrical conductivity and long-term humidity and thermal stability still require further improvement. Benefiting from its outstanding water dispersibility and inherent stretchability, PEDOT:PSS overcomes the rigidity limitations of traditional conductive materials, [36–38] and successfully constructs a three-dimensional conductive network within the hydrophilic hydrogel matrix that can accommodate deformation while maintaining electrical continuity, thereby providing a fundamental guarantee for reliable strain sensing (Fig. 3a).

Table 1: Comparison of sensing performance of various strain sensors.

Material System	Working Range	Sensitivity	Ref.
PVA/CNT	0%–200%	1.2 (0%–100%) 1.7 (100%–200%)	[39]
PAM/SA/CNT/LM	0%–600%	2.56 (0%–200%) 7.53 (200%–600%)	[40]
ASmylopectin/PVA/Borax/MXene	0%–300%	1.1	[41]
WS/LM/P(NAGA-co-AAm)/PNWLG	0%–1159%	4.17 (0%–795%) 15.08 (795%–1159%)	[42]
LMA/TPEE/PAM/VBiBr	0%–1300%	1.33	[43]
PVA/LM/TA	0%–710%	3.86	[44]
BLG/Ag/PVA/PAA	0%–400%	1.7 (0%–100%) 2.6 (100%–400%)	[45]
Gel/SA/PNIPAM/Fe^{3+}/$(NH_4)_2SO_4$	0%–250%	2.048	[46]
PAM/Laponite/H_3BO_3/EG	0%–750%	2.68	[47]
PAM/PEDOT:PSS/Gly	1%–600%	3.25	[48]
P(AM-co-MA)/PEDOT:PSS	0%–1400%	3.42 (0%–600%) 6.85 (600%–1400%)	[49]
PAM/PVA/PEDOT:PSS/MXene	0%–772%	5.16	[50]

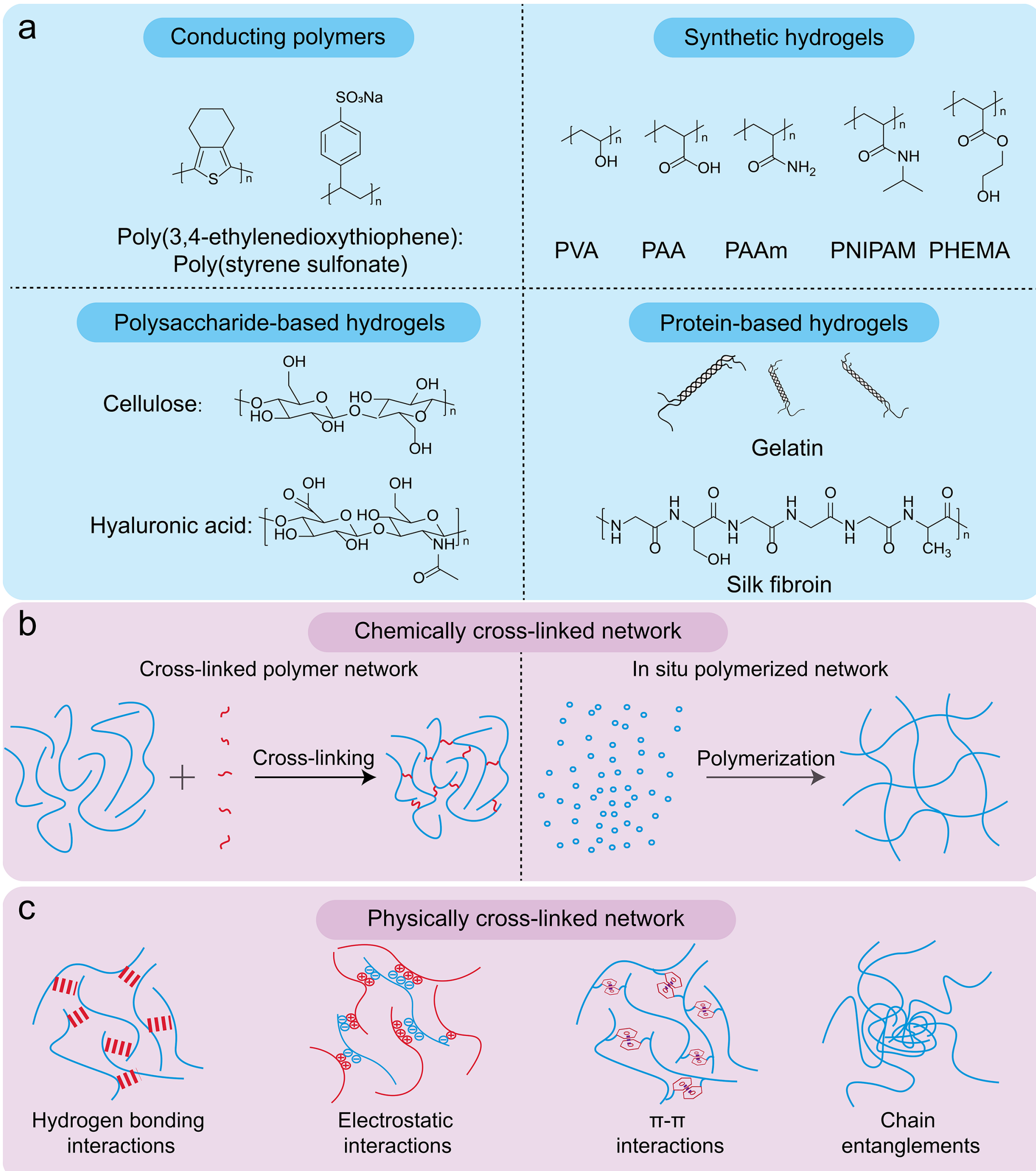


Figure 3: The basic composition of PEDOT:PSS hydrogels and the principles of different crosslinking mechanisms. (**a**) Structural formulas of PEDOT:PSS and various hydrogels. (**b**) Mechanism of chemical cross-linking in hydrogel networks. (**c**) Mechanism of physical cross-linking in hydrogel networks.

The selection of the hydrogel matrix directly determines the mechanical properties and functional dimensions of the sensor, and can be primarily categorized into the following three types: Synthetic hydrogels, represented by polyvinyl alcohol (PVA), polyacrylic acid (PAA), and polyacrylamide (PAM). Through precise molecular design and cross-linking modulation, these materials possess highly tunable modulus, excellent elasticity, and durability [51]. Among them, PEDOT:PSS/PVA hydrogels have achieved a broad strain range [52]. In another study, a hydrogel-based strain-temperature bimodal flexible sensor (gauge factor of 10.25) was fabricated using a PAM/CS hydrogel substrate coated with PEDOT:PSS [53]. Natural hydrogels are further divided into polysaccharide-based (e.g., cellulose, sodium alginate, hyaluronic acid) and protein-based (e.g., gelatin, silk fibroin) hydrogels [54,55]. For instance, a biomimetic adhesive hydrogel was constructed via a one-pot method by compositing sodium alginate, trehalose, and PEDOT:PSS, achieving a sensitivity of 185.90 and a response time of 150 ms when used as a strain sensor [56]. These materials typically possess inherent biocompatibility, environmental degradability, and abundant functional groups, offering unique advantages for the direct application of sensors in biomedical fields.

Water, as the primary solvent component of hydrogels, plays a crucial role in PEDOT:PSS hydrogel strain sensors, with its content and retention capability profoundly affecting the mechanical properties, electrical properties, and long-term operational reliability of the material. Water molecules play a dual role in the system: on the one hand, high water content ensures mechanical flexibility, but excessive water can lead to swelling and disruption of the conductive network, resulting in a decrease in conductivity; on the other hand, water evaporation and loss represent one of the main mechanisms underlying sensor performance degradation, as water loss can induce volume shrinkage, deterioration of mechanical properties, and damage to the conductive network, ultimately leading to signal drift or failure.

These hydrogel materials form stable three-dimensional network structures through two types of mechanisms (Fig. 3b,c): Chemical cross-linking, which involves connecting polymer long chains via covalent bonds or directly polymerizing monomers to form a permanent network with stable mechanical properties [57–59]; Physical cross-linking, which relies on reversible non-covalent interactions, such as hydrogen bonding, electrostatic interactions, π-π stacking, and physical entanglement of polymer chains, endowing the network with self-healing or stimulus-responsive properties [60–62].

3 Fabrication Methods of PEDOT:PSS Hydrogel Strain Sensors

In the research of PEDOT:PSS hydrogel strain sensors, the innovation and selection of processing techniques are crucial for enabling the functional and integrated applications of such devices [63,64]. Currently, processing strategies ranging from one-dimensional to three-dimensional approaches provide multi-layered manufacturing solutions for the development of these sensors.

One-dimensional microfluidic spinning technology offers an effective method for fabricating high-performance conductive fibers. For example, Sun et al. utilized a coaxial microfluidic device to prepare strain-insensitive conductive fibers with a helical structure by leveraging the heterogeneous solidification process of PVA-PEDOT:PSS and PU solutions, combined with the rope coiling effect [65]. These fibers exhibit less than 5% resistance variation under 500% tensile deformation, demonstrating excellent electrical stability and providing new insights for the design of one-dimensional stretchable sensors (Fig. 4a). Two-dimensional screen printing technology holds significant advantages for patterning flexible substrates. Li et al. developed a ternary conductive ink based on PEDOT:PSS, graphene, and carbon black, achieving high-resolution direct printing of sensing patterns on textile surfaces through the optimization of printing parameters [66]. This process is highly compatible with textile manufacturing workflows, offering a feasible technological pathway for the large-scale production of smart textiles (Fig. 4b). Three-dimensional direct ink writing technology further advances the development of sensors toward integration and customization. Wang et al., utilizing a PEDOT:PSS composite ink with shear-thinning properties, achieved integrated manufacturing from flexible substrates to functional layers through a multi-material layered printing strategy [67]. This method supports the free construction of complex three-dimensional structures, demonstrating unique value in specialized applications such as plant physiological monitoring (Fig. 4c).

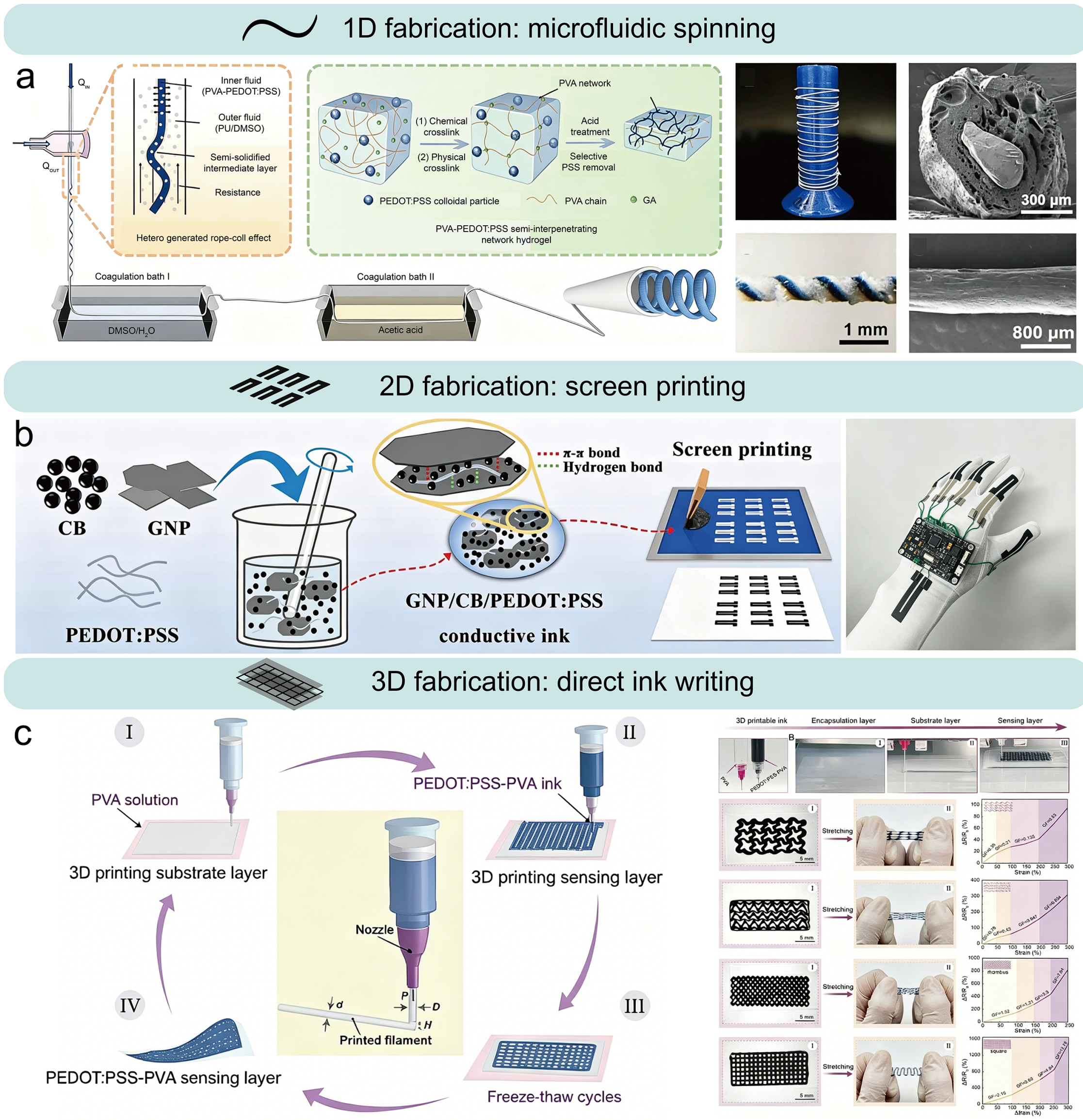


Figure 4: Schematic diagrams of processing methods for PEDOT:PSS hydrogel strain sensors. (**a**) One-dimensional microfluidic spinning technology. Reprinted/adapted with permission from reference [65]. Copyright 2025, copyright Springer Nature Link. (**b**) Two-dimensional screen printing technology. Reprinted/adapted with permission from reference [66]. Copyright 2025, copyright ACS publications. (**c**) Three-dimensional direct ink writing technology. Reprinted/adapted with permission from reference [67]. Copyright 2025, copyright OAE Publishing Inc.

Recent advances in emerging fabrication techniques also include the development of more diverse 3D printing technologies. By combining laser direct writing with 3D printing and optimizing the laser parameters and printing processes [68], researchers have obtained a patterned flexible strain sensor with composite microstructures. The sensitivity of this sensor was improved by 339% compared to its unpatterned counterpart, the response time was shortened to 140 ms, and it exhibited excellent cyclic stability. Direct ink writing technology has been further extended to the field of 4D printing [69]. An ultra-flexible sensor with multi-responsive capabilities to strain, temperature, and magnetic fields was fabricated using direct ink writing (DIW). This technology not only achieves a linear strain range of 350% and a fast response time of 83 ms, but also supports freeform fabrication of complex geometries, providing great flexibility in the structural design of multifunctional sensors. Aerosol jet printing (AJP) technology excels in micron-scale high-precision patterning [70]. Complex patterns with a resolution of 12 μm were achieved using AJP. The resulting flexible strain sensor exhibited a detection limit as low as 0.0033% and a sensing range up to 660%, enabling accurate detection of various physiological signals such as pulse, speech, facial expressions, and joint movements.

4 Performance of PEDOT:PSS Hydrogel Strain Sensors

4.1 Mechanical Properties

The practical application effectiveness of PEDOT:PSS hydrogel strain sensors is jointly determined by their mechanical and electrical properties. Among these, mechanical performance serves as the fundamental prerequisite for sensor functionality, directly influencing device compatibility with biological tissues or dynamic surfaces, deformation adaptability, and structural longevity [71–73]. Current research focuses on synergistically optimizing mechanical performance in key dimensions-such as expanding strain range, enhancing tensile strength, and improving fatigue resistance-through innovative material design and fabrication strategies. At the same time, efforts are made to ensure the stability and reliability of electrical performance, thereby driving the development of sensors toward higher performance and extended service life.

In terms of enhancing mechanical performance, to simultaneously expand the strain range and increase tensile strength, multi-network synergy and microstructural design have emerged as critical pathways. For example, Zhao et al. proposed a dual-network enhancement strategy based on an intrinsically conductive polymer and polyacrylamide (PAM) [74]. In this strategy, hydroxyethyl cellulose (HEC) is first modified with allyl groups to obtain AHEC, which is then polymerized with EDOT and composited with PEDOT:PSS to form a reticulated conductive component, AHEC-PP. Subsequently, an AHEC-PP/PAM dual-network hydrogel is constructed. The two networks are tightly intertwined through multiple physical interactions, including hydrogen bonding, electrostatic interactions, and π-π stacking. The resulting hydrogel exhibits a fracture strain of 1273% and a toughness of 2.35 MJ m^{-3} (Fig. 5a). Meanwhile, Tang et al.'s "protein unfolding-chemical coupling strategy" targeting biomedical applications, achieved a balance between high tensile strength and excellent biocompatibility in a pure protein system through synergistic thermo-induced protein physical crosslinking and chemical coupling [75]. This approach offers a new material paradigm for bio-integrated electronics (Fig. 5b).

To meet the durability requirements for long-term dynamic monitoring, enhancing the long-term stability of sensors is crucial. A significant breakthrough has been achieved with the freeze-casting combined with salting-out strategy [32]. This work constructs a highly ordered lamellar orientation structure through directional freezing, combined with salting-out treatment to induce polymer crystallization, effectively increasing the physical crosslinking density and crack propagation resistance. In notched tests, the materials maintained crack non-propagation after tens of thousands of cyclic stretches, achieving a fatigue threshold as high as 300 J m^{-2} (Fig. 5c). This outcome not only demonstrates that precise microstructural engineering can significantly enhance the mechanical reliability of PEDOT:PSS hydrogel sensors while endowing them with excellent long-term stability, but also further proves the positive contribution of mechanical enhancement strategies to sensing performance-by improving mechanical toughness and stability, the strain range is effectively broadened, hysteresis is reduced, and cyclic stability is enhanced. Benefiting from the ordered hydrogel network constructed by this strategy, the sensor achieves cyclic stability exceeding 10,000 cycles and a hysteresis as low as 4%.

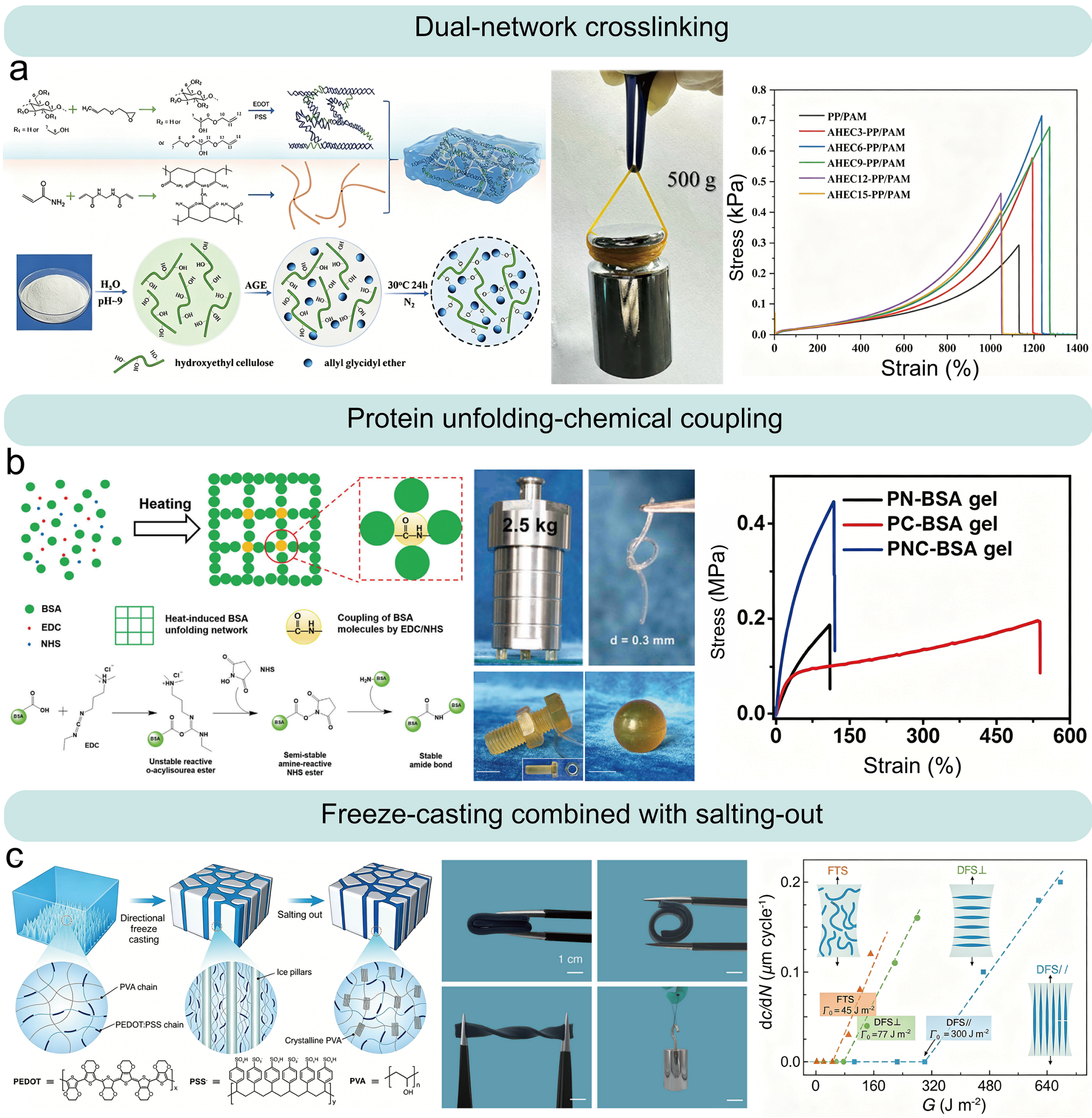
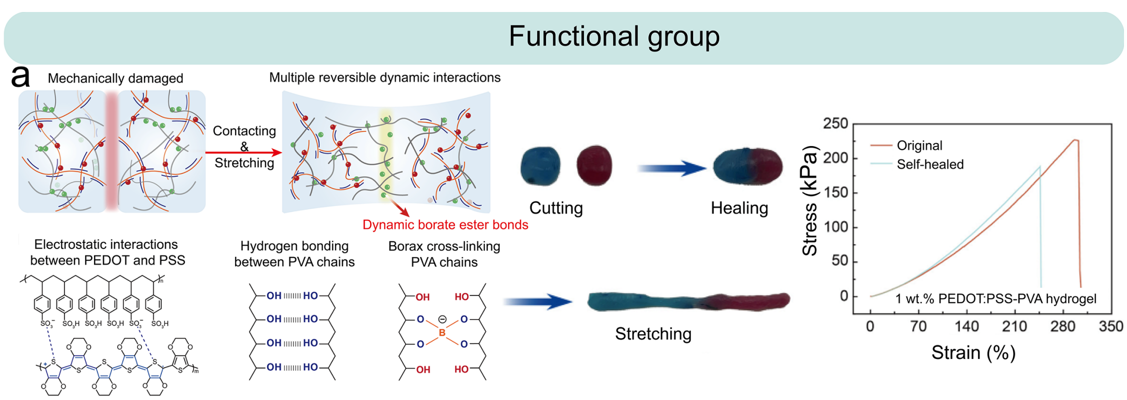


Figure 5: Mechanical enhancement strategies for PEDOT:PSS hydrogel strain sensors. (**a**) Dual-network crosslinking strategy of AHEC-PP/PAM hydrogel, where the reticulated conductive component AHEC-PP is intertwined with the PAM network through multiple physical interactions. Reprinted/adapted with permission from reference [74]. Copyright 2024, copyright Cell Press. (**b**) Protein unfolding-chemical coupling strategy integrating thermally induced physical networks with EDC/NHS chemical crosslinking. Reprinted/adapted with permission from reference [75]. Copyright 2021, copyright Wiley. (**c**) Freeze casting and salting-out synergistic strategy utilizing ice templates for directed PVA crystal formation. Reprinted/adapted with permission from reference [32]. Copyright 2023, copyright Wiley.

4.2 Self-Healing Properties

In the field of flexible electronics, self-healing capability is regarded as a revolutionary characteristic that enhances device durability and reliability [76,77]. For most traditional solid-state materials, achieving autonomous functional recovery after damage is nearly impossible. However, soft and wet materials such as PEDOT:PSS hydrogels exhibit unique advantages. Their three-dimensional polymer network structures, rich in intermolecular forces and functional groups, provide an ideal platform for constructing multiscale dynamic and reversible interactions. By carefully designing dynamic crosslinking networks across different scales, researchers have successfully endowed these sensors with the ability to autonomously restore their structural and electrical functions after mechanical damage, overcoming the limitation of "single damage leading to failure" in traditional electronic devices.

At the molecular/group level, Cao et al. introduced dynamic covalent bonds (boronic ester bonds) and synergistic multiple non-covalent interactions (hydrogen bonds, electrostatic interactions) to successfully develop PEDOT:PSS-PVA hydrogels with rapid self-healing capability [78]. This material can autonomously repair itself within just 30 s of contact at room temperature, achieving a stress recovery rate of over 83.5%, while its resistance can rapidly return to the initial state within 0.23 s (Fig. 6a). At the chain/segment level, Yang et al., based on a gelatin/PVA hydrogen bond network, enhanced chain segment mobility by introducing the ionic liquid BMIM-BF4 and maintained a moist environment using glycerol [33]. PEDOT:PSS not only provides conductive functionality but also participates in the construction of reversible crosslinking networks through dynamic hydrogen bonds or electrostatic interactions formed between its sulfonate groups (-SO_3^-) and hydrogen bond donors in the hydrogel matrix (hydroxyl groups of PVA). When the material is damaged, these dynamic bonds can spontaneously reassociate, enabling simultaneous restoration of both the conductive pathways and the mechanical network. This enabled the hydrogel to rapidly reconstruct conductive pathways within approximately 260 ms after damage, with mechanical properties after healing nearly matching the original state (Fig. 6b). At the dynamic structural domain level, Lu et al. constructed hydrophobic association microdomains by introducing hydrophobic monomers (HMA) into the polymer network, supplemented by interactions such as hydrogen bonds, achieving a self-healing system based on dynamic physical crosslinking [79]. PEDOT:PSS forms nanoscale conductive domains via π-π stacking interactions, which are embedded into the hydrogel network as physical crosslinking points. After material damage, the non-covalent interactions between these domains can be re-established, not only restoring mechanical integrity but also reconstructing the three-dimensional conductive pathways, thereby ensuring rapid recovery of sensing functionality. Research shows that the addition of glycerol significantly improves healing efficiency, with elongation recovery increasing from 22.7% to 36.4% after 24 h at room temperature, while heating at 60°C further enhances the healing process (Fig. 6c).



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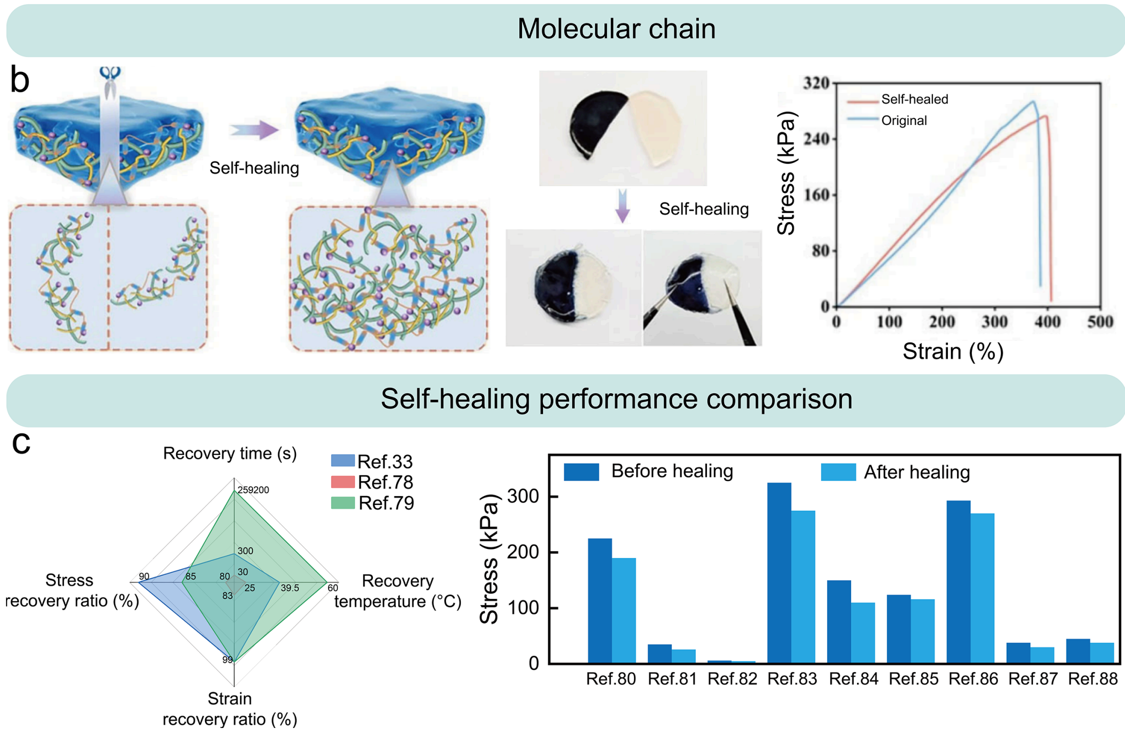


Figure 6: Design strategies for self-healing properties in PEDOT:PSS hydrogel sensors. (**a**) Multiphase reversible dynamic interaction strategy. Reprinted/adapted with permission from reference [78]. Copyright 2023, copyright MDPI. (**b**) Chain-segment level self-healing hydrogels. Reprinted/adapted with permission from reference [33]. Copyright 2025, copyright ACS Publications. (**c**) Comparison of stress recovery ratio, strain recovery ratio, recovery time, and healing temperature for different strategies.

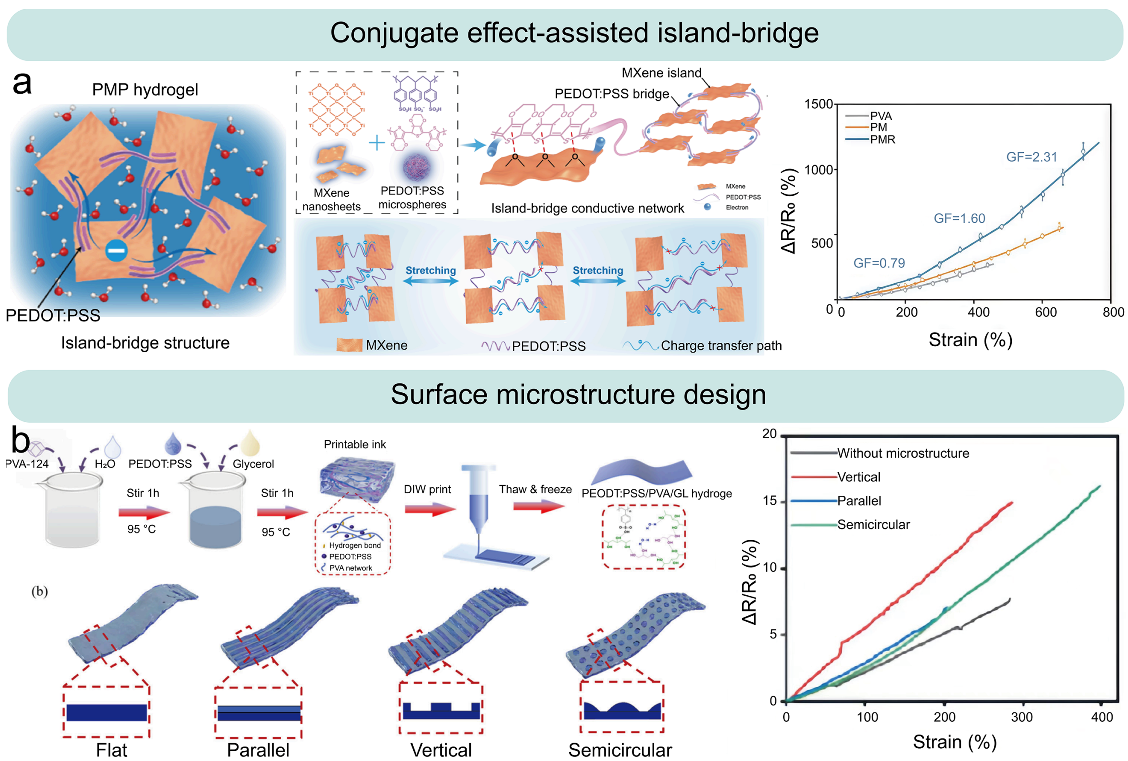
Analyzing healing performance parameters reveals distinct differences among strategies: molecular-level strategies based on dynamic covalent bonds achieve the fastest healing (within seconds) and higher mechanical recovery rates; hydrogen bond network strategies at the chain segment level enable millisecond-level reconstruction of conductive pathways; while structural domain strategies based on hydrophobic association exhibit relatively longer healing times but can be significantly accelerated with thermal stimulation. According to existing literature, stress recovery rates of self-healing hydrogels generally range between 70% and 95%, [80–84]. with healing times spanning from seconds to tens of hours, depending primarily on the type of dynamic interactions, environmental conditions, and the application of external stimuli [85–88].

4.3 Sensing Performance

4.3.1 Sensitivity

To collaboratively address the trade-off between sensitivity and detection range, researchers have systematically explored various dimensions such as network structure reconstruction, transmission mechanism innovation, and bio-inspired topological design [89–91].

At the level of conductive network structure, Ding et al. proposed a binary conductive system based on “MXene island-PEDOT:PSS bridge”. This system utilizes a polyacrylamide (PAM) hydrogel matrix, in which PEDOT:PSS serves as the primary conductive component, forming a continuous conductive network that bridges MXene nanosheets through interfacial p-π interactions [92]. By leveraging these interactions to stabilize the network and inducing a hierarchical dissociation mechanism under strain, they achieved a stepwise enhancement in sensitivity (GF ranging from 0.79 to 2.31) across a broad strain range of 0%–763% (Fig. 7a). In terms of surface microstructure design, Chen et al., inspired by the morphology of annelid skin, constructed a bioinspired ridge-shaped microstructure on the surface of a PEDOT:PSS/PVA/glycerol hydrogel using DIW printing technology for controllable fabrication [93]. This microstructure generates a significant stress concentration effect during stretching, leading to more severe damage to the local conductive network, thereby achieving a greater resistance change under the same strain. Finite element analysis verified this mechanism. Benefiting from this strategy, the sensor exhibits a high gauge factor of 5.1, a tensile range of 300%, and a linearity of 0.99 (Fig. 7b). In terms of the crack deformation strategy, Yao et al. proposed a closed-loop localized crack strain sensor. By prefabricating a controllable crack in a hydrogel fiber loop, they achieved a synergistic effect between the crack opening/closing effect and the geometric deformation effect [30]. During stretching, the opening and closing of the crack lead to rapid switching of the conductive path, resulting in a drastic resistance change and thus an ultrahigh sensitivity (GF up to 3930). After the crack is fully opened, the geometric deformation of the hydrogel fiber itself continues to contribute to the resistance change, ensuring a wide detection range of 0.02% to 80% (Fig. 7c).



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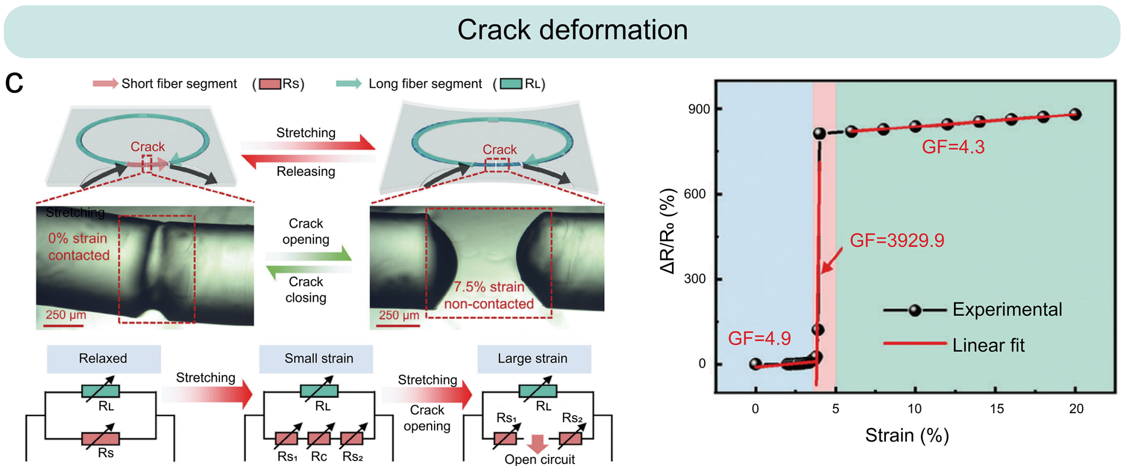


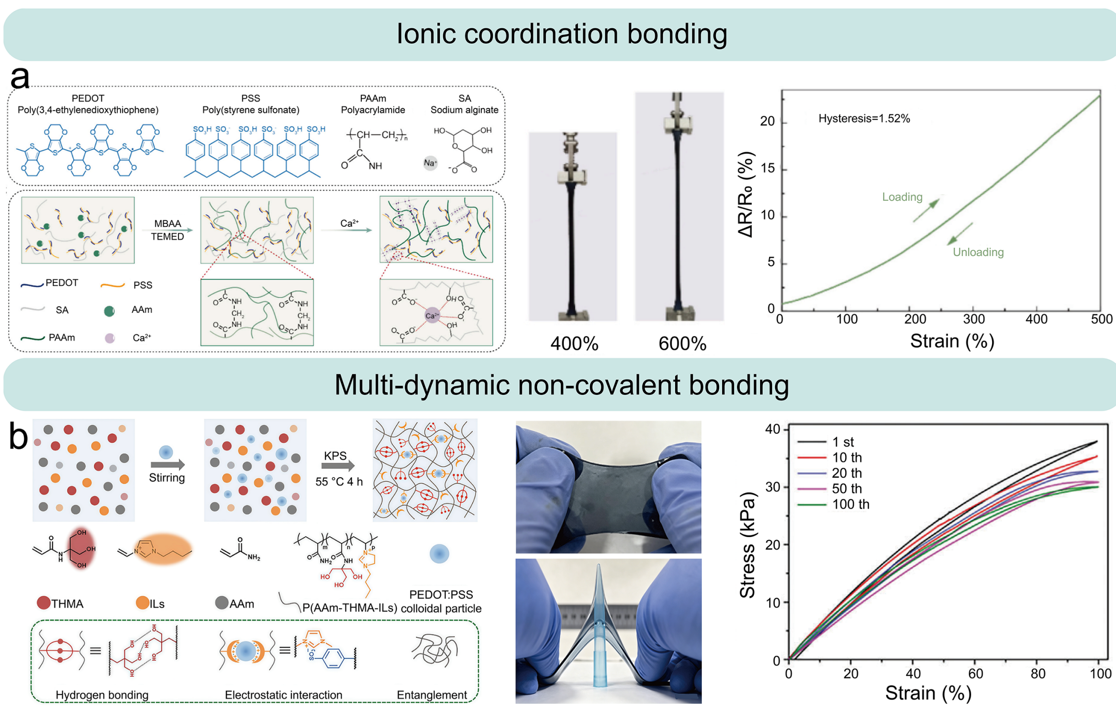
Figure 7: Design strategies for high sensitivity in PEDOT:PSS hydrogel sensors. (**a**) Conjugated island-bridge network, sliding dissociation of bridges under strain induces sensitive resistance changes. Reprinted/adapted with permission from reference [92]. Copyright 2025, copyright ACS Publications. (**b**) Surface microstructure: stress concentration aggravates local conductive network damage, enhancing strain sensitivity. Reprinted/adapted with permission from reference [93]. Copyright 2025, copyright ACS Publications. (**c**) Closed-loop localized crack (CLC): synergy of crack opening/closing and geometric deformation achieves ultrahigh sensitivity of 3930. Reprinted/adapted with permission from reference [30]. Copyright 2025 copyright Wiley.

Among the strategies described above, the conductive network structure reconstruction strategy and the crack deformation strategy demonstrate significant advantages in PEDOT:PSS-based hydrogel systems. The former achieves tunable sensitivity over a wide strain range through interfacial interactions and a hierarchical dissociation mechanism. The latter, leveraging the synergistic effect of crack opening/closing and geometric deformation, trikes an excellent balance between ultrahigh sensitivity and a broad detection range.

4.3.2 Hysteresis

Hysteresis is a key metric for evaluating the reversibility and reliability of strain sensor responses, referring to the phenomenon where loading and unloading curves do not coincide during cyclic loading-unloading processes. Low hysteresis characteristics indicate that the sensor possesses rapid and accurate signal recovery capabilities, which are crucial for achieving precise, real-time human motion monitoring and biological signal recognition [94–96]. In contrast, high hysteresis can lead to signal distortion and response delays, severely limiting the practical application accuracy and reliability of sensors. In recent years, strategies such as dynamic bonding and network structure optimization have significantly improved the hysteresis of PEDOT:PSS hydrogel strain sensors.

To effectively reduce sensing hysteresis, research has focused on minimizing irreversible energy dissipation by regulating the dynamic response and microstructure of materials. The core strategies lie in introducing dynamic reversible interactions and optimizing the network phase morphology. At the dynamic bonding level, constructing reversible cross-linking points within the hydrogel network enables effective energy dissipation and rapid structural recovery during deformation. For example, Cao et al. achieved a hysteresis rate as low as 1.52% by incorporating dynamic ion coordination bonds cross-linked by Ca^{2+} in a dual-network system, allowing reversible breaking and reformation of ionic bonds under cyclic strain, along with excellent cycling stability (Fig. 8a) [78]. From the perspective of molecular chain interactions, the multi-dynamic non-covalent bonding synergy strategy provides a more comprehensive approach to optimizing hysteresis performance. Wang et al. constructed a multi-dynamic non-covalent bonding network by introducing triple hydrogen-bonding clusters, electrostatic interactions from ionic liquids, and chain entanglements into a PEDOT:PSS-based hydrogel [97]. This design avoided the high energy dissipation typically caused by sacrificial bonds in traditional high-strength hydrogels, achieving a stable hysteresis ratio of 4%–5.5% over a strain range of up to 800%, with a residual strain of <3% and a stress recovery rate of 98.5% after 100 cycles (Fig. 8b). In addition, Wibowo et al. proposed a synergistic strategy: enhancing molecular chain mobility with plasticizers such as glycerol to reduce viscous resistance, while simultaneously providing a stable network skeleton through covalent crosslinking with glutaraldehyde to inhibit permanent deformation [98]. This synergistic approach achieved a hysteresis degree as low as 0.79% at 50% strain, enabling highly reversible resistance responses. In terms of phase morphology regulation, designing specific microphase structures to suppress chain slippage and interfacial dissipation is another effective approach. Shen et al. employed a microphase semi-separation strategy to construct a structure where PEDOT-enriched conductive phases and PVA-crosslinked mechanical phases are interlocked [31]. This tightly coupled microphase significantly reduces interfacial slippage during cyclic deformation, maintaining the hysteresis rate below 1.5% even at strains up to 300%, while achieving favorable response linearity (Fig. 8c).



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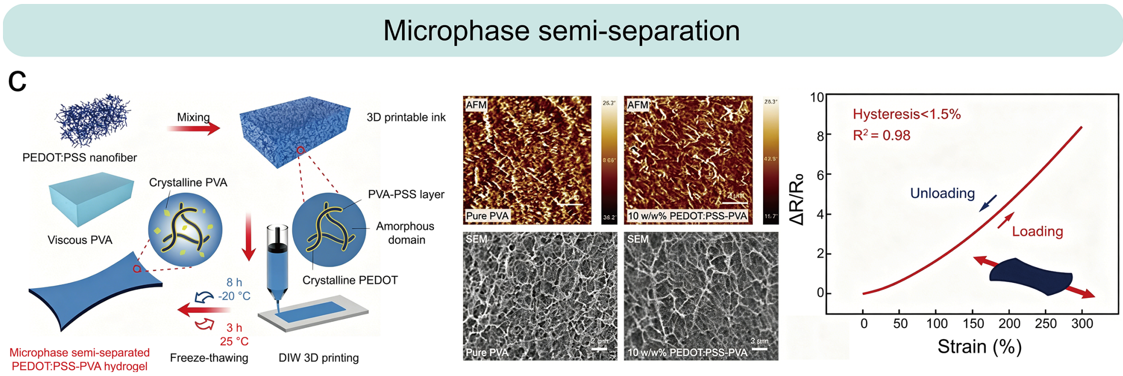

Figure 8: Design strategies for low hysteresis in PEDOT:PSS hydrogel sensors. (**a**) Ionic coordination dynamic crosslinking through Ca^{2+} networks achieves low hysteresis response and stable signal output under strain. Reprinted/adapted with permission from reference [78]. Copyright 2024, copyright Elsevier. (**b**) Multi-dynamic non-covalent bonding synergy strategy. One-pot synthesis schematic, hydrogel photograph, multi-dynamic interactions (hydrogen bonding, electrostatic interactions, chain entanglements), and 100-cycle tensile curves at 100% strain showing ultra-low hysteresis [97]. Copyright 2024, copyright Wiley. (**c**) Microphase semi-separated ordered structures with distinct PVA crystalline domains and PEDOT:PSS amorphous phases provide printed devices with low-hysteresis sensing capability. Reprinted/adapted with permission from reference [31]. Copyright 2022, copyright Wiley.

4.4 Synergistic Design of Multiple Properties

Significant progress has been made in optimizing individual dimensions of PEDOT:PSS-based hydrogels, such as mechanical properties, sensing performance, and self-healing properties. However, integrating these multiple properties into a single hydrogel system remains a considerable challenge. Different properties often exhibit trade-off relationships: high sensitivity typically relies on easily disrupted conductive networks, which may compromise mechanical stability; while dynamic crosslinking endows self-healing capability, it may affect mechanical properties. Therefore, achieving synergistic design across mechanical properties, sensing performance, and self-healing properties has become a critical scientific issue for the practical application of this field.

In terms of synergistic design, an innovative "3D super-interface" structural design strategy offers a new approach to resolving the conflict between high sensitivity and wide strain range [99]. By constructing a conductive crack layer on a patterned rubber substrate, this strategy achieves a gauge factor as high as 1.1×10^8 within a small strain range of 0%–10%, with a linearity of 0.98, while maintaining a wide strain response range of over 100%, thus thoroughly addressing the core challenge of achieving both high sensitivity and a broad response range. This work demonstrates that fine interfacial structural design enables synergistic optimization across multiple performance metrics.

5 Applications of PEDOT:PSS Hydrogel Strain Sensors

5.1 Human Motion Monitoring

Human motion monitoring stands as one of the most promising application domains for PEDOT:PSS hydrogel strain sensors. Leveraging their excellent mechanical compliance, high sensitivity, and favorable biocompatibility, these sensors enable real-time and precise monitoring of various physiological and motion signals [100,101]. Studies have shown that such sensors excel in real-time monitoring of large-scale limb movements. Yuan et al. achieved direct printing onto elastic fabric by printing PEDOT:PSS ink onto a pre-stretched nylon fiber-wrapped rubber band, taking advantage of its excellent aqueous dispersibility and solution processability. The pre-stretched structural design effectively suppresses transverse deformation, thereby enabling high-fidelity dynamic strain monitoring. This sensor exhibits a sensing range of 40%, a hysteresis error of 2.8%, and a cyclic stability exceeding 10,000 cycles. Through textile-integrated deployment, the sensor accurately captures knee joint motion parameters with a signal fidelity exceeding 97%, providing a high-precision monitoring solution for gait analysis and rehabilitation training (Fig. 9a) [102].

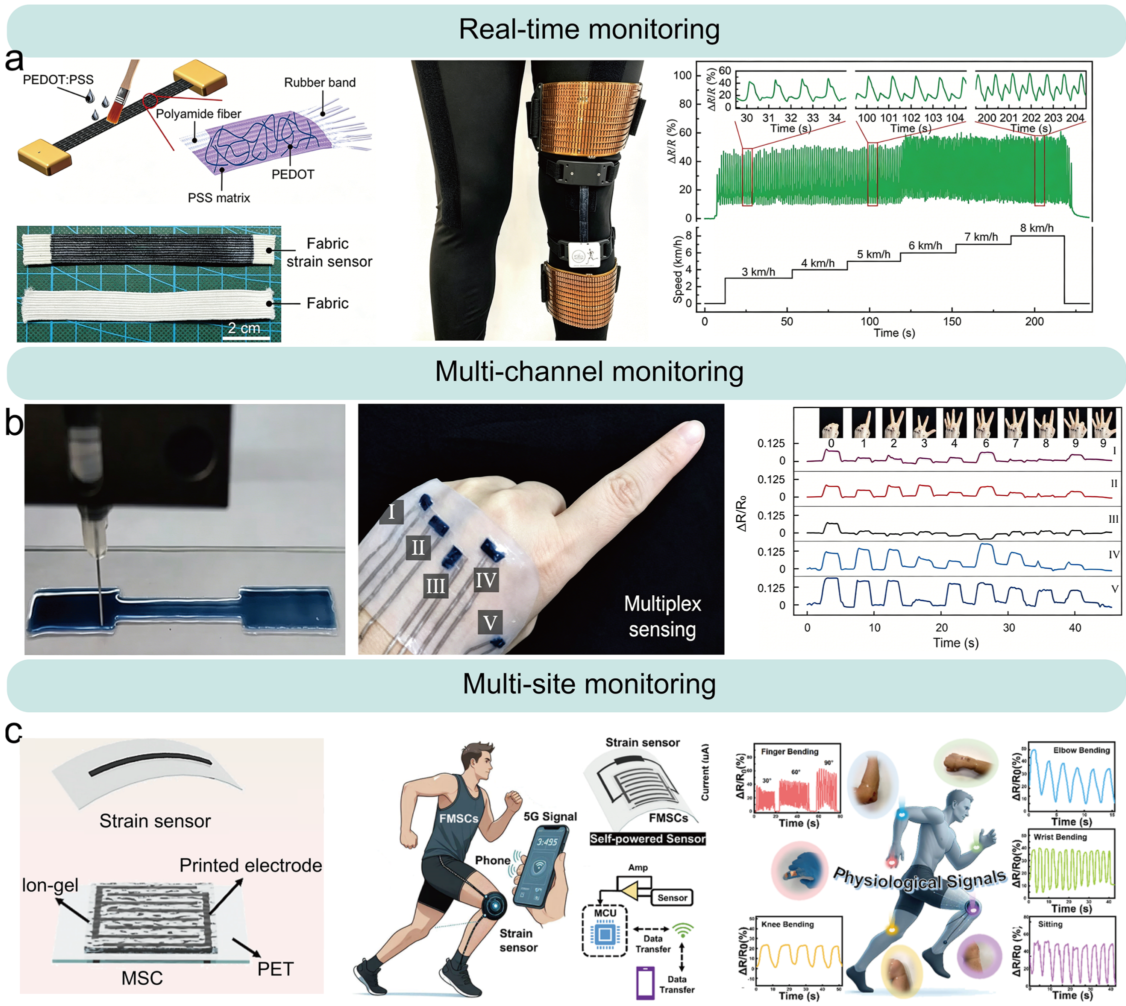

Figure 9: Human motion detection applications of PEDOT:PSS hydrogel sensors. (**a**) Flexible PEDOT:PSS/rubber composite multilayer sensing structure enables self-powered monitoring of dynamic strain and resistance response during running leg movements. Reprinted/adapted with permission from reference [102]. Copyright 2023, copyright Wiley. (**b**) Self-powered joint strain sensor integrated with wireless module collects real-time joint bending signals and transmits them to mobile devices for remote motion monitoring. Reprinted/adapted with permission from reference [31]. Copyright 2024, Copyright 2022, copyright Wiley. (**c**) Multiplexed sensor array based on conducting polymer hydrogels identifies multiple hand gestures to achieve high-precision gesture monitoring and recognition. Reprinted/adapted with permission from reference [103]. Copyright ACS Publications.

Meanwhile, in the field of multi-channel monitoring of fine motions, Shen et al. designed a microphase semi-separated network structure by compositing PEDOT:PSS nanofibers with PVA, achieving a high stretchability of 300% and enabling the detection of minute strains as low as 0.05%, combining excellent mechanical compliance with high sensitivity. Based on this, they developed a multi-channel sensor array system capable of real-time tracking of high-resolution movements such as finger bending and gesture recognition, demonstrating its potential in barrier-free interaction and human-machine control (Fig. 9b) [31].

From the perspective of technological evolution, current research is advancing this field toward systematic, intelligent, and multi-site monitoring platforms. Sun et al. composited 0D carbon quantum dots (CQDs) with 1D multiwalled carbon nanotubes (MWCNT), incorporating PEDOT:PSS as a dispersant and PEO as a binder. The addition of PEDOT:PSS effectively enhances the uniformity and rheological properties of the ink, enabling high-precision dispensing printing, and the resulting strain sensor achieves a high gauge factor (GF) of 94.1. Although their study is based on a carbon-based material system, their work in constructing an integrated system architecture combining energy harvesting, signal processing, and wireless transmission offers valuable insights for the systematic integration of PEDOT:PSS hydrogel sensors [103]. By deeply integrating sensors with flexible energy modules and edge computing units, researchers have successfully developed intelligent monitoring platforms with capabilities such as self-powering and multimodal signal processing (Fig. 9c).

5.2 Human-Computer Interface

Human-machine interaction aims to build efficient and intelligent bidirectional information channels. Leveraging their flexibility, conformability, and high sensitivity, PEDOT:PSS hydrogel strain sensors have become core materials for next-generation interactive interfaces, capable of accurately recognizing human motion intent and endowing machines with environmental perception capabilities [104–106]. Its millisecond-level fast response enables real-time capture of gesture changes and tactile stimuli, ensuring low-latency signal transmission. Its excellent flexibility allows conformal adhesion to the skin, maintaining stable electrical contact under dynamic deformation, thereby enhancing wearing comfort and signal reliability. Its high sensitivity (GF > 10) enables precise detection of subtle muscle movements and gesture changes, providing strong support for fine manipulation and complex command recognition.

In the field of environmental perception and object recognition, Hu et al. developed a composite hydrogel sensor integrating piezoresistive and piezoelectric responses, which can simultaneously capture static deformation and dynamic force information during grasping [107]. By analyzing resistance and voltage signals, the system effectively distinguishes object contours, providing key technical support for robotic tactile systems (Fig. 10a). In the domain of direct machine control, Hao's team integrated multifunctional hydrogel sensors into smart gloves, enabling wireless control of devices through finger bending movements [108]. These sensors feature millisecond-level response speed and excellent environmental stability, ensuring reliable signal transmission in complex scenarios (Fig. 10b). In the field of smart healthcare and rehabilitation applications, Zhao et al. developed an intelligent rehabilitation system that integrates sensing, assessment, and training functions into a single platform [109]. The system is based on a PVA/PNIPAM/PEDOT:PSS conductive hydrogel sensor, which leverages its fast response time (200 ms), low detection limit (1% strain), and excellent cyclic stability to enable real-time monitoring of finger joint movements in patients. Patients can interact with the system simply through natural finger bending, without the need for additional operations. The collected rehabilitation data can be saved in real time or wirelessly transmitted to physicians, facilitating remote diagnosis and rehabilitation program adjustment. This work provides a comprehensive solution that integrates monitoring, assessment, and training within a human-machine interaction framework for remote personalized rehabilitation, significantly optimizing the utilization of medical resources and paving new pathways for the development of smart rehabilitation medicine (Fig. 10c).

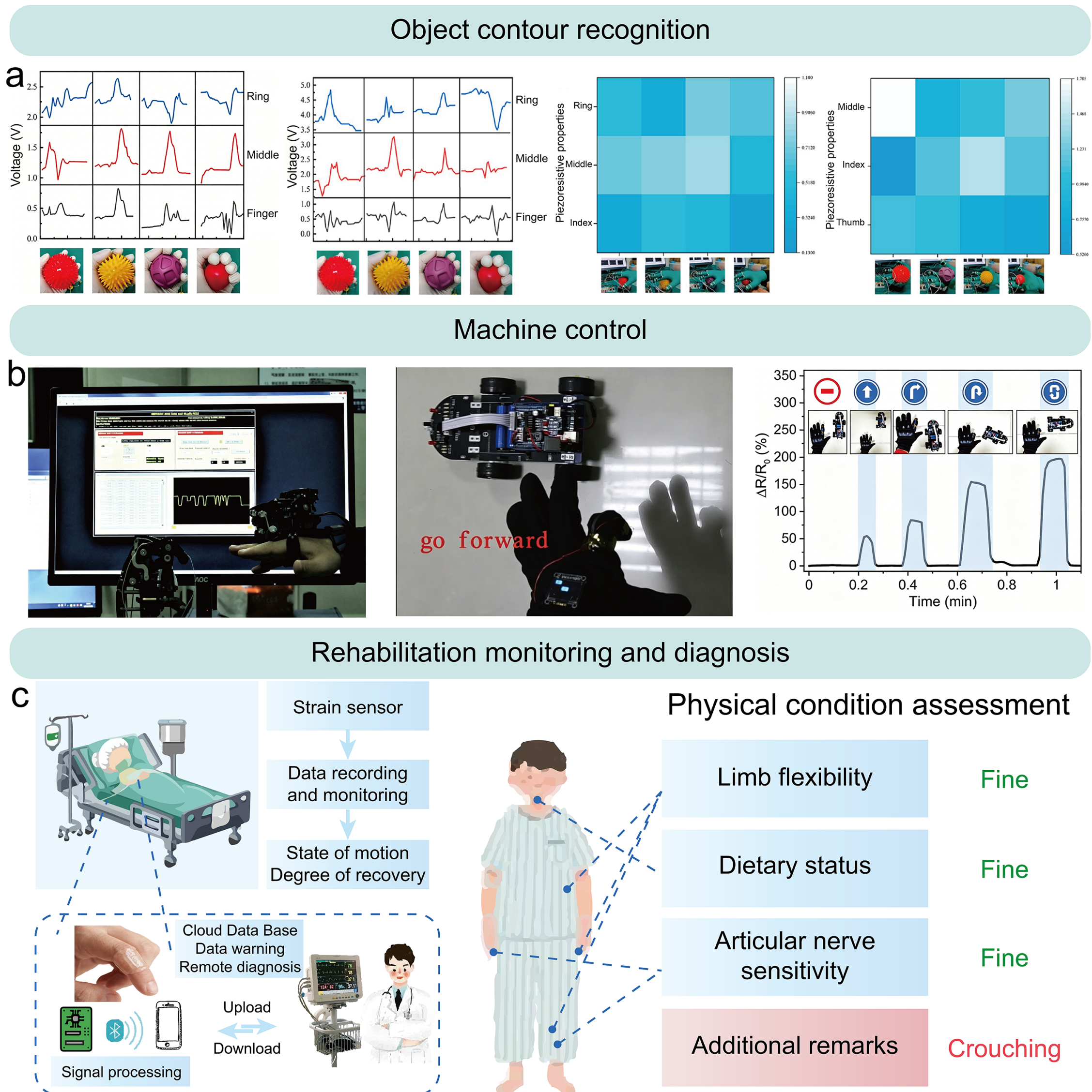

Figure 10: Applications of PEDOT:PSS hydrogel strain sensors in human-machine interaction. (**a**) Multimodal sensing for robotic tactile systems, where piezoresistive and piezoelectric responses enable object contour recognition through combined analysis of resistance and voltage signals. Reprinted/adapted with permission from reference [107]. Copyright 2022, copyright ACS Publications. (**b**) Smart glove-based wireless control interface, translating finger bending movements into device control commands with millisecond-level response speed and environmental stability. Reprinted/adapted with permission from reference [108]. Copyright 2021, copyright RSC Publications. (**c**) Integrated intelligent rehabilitation system, providing real-time joint motion monitoring and visual feedback for personalized training and quantitative assessment of recovery progress. Reprinted/adapted with permission from reference [109]. Copyright 2024, copyright Springer.

5.3 Plant Growth Monitoring

In the fields of precision agriculture and plant phenotyping research, achieving non-destructive, continuous, and high-precision monitoring of plant growth processes is of great significance. PEDOT:PSS hydrogel strain sensors, leveraging their high sensitivity, excellent flexibility, and biocompatibility, provide an innovative sensing solution for this field, enabling real-time *in-situ* monitoring of multi-dimensional and multi-parameter plant growth processes [110–113].

Faster and more direct plant surface monitoring technologies have also been developed. Hild et al. utilized DIW technology to directly print the conductive polymer PEDOT:PSS and the flexible Block 6 onto the surfaces of living tobacco leaves [35]. Both materials exhibited good biocompatibility, caused no obvious plant stress, and remained stable on the leaves for over 28 days. This study provides a new fabrication strategy for the development of low-toxicity, non-invasive plant sensors and biohybrid systems (Fig. 11a). For multi-dimensional growth quantification and integrated sensing, Wang et al. utilized fully 3D printing integration technology to develop a hydrogel strain sensor capable of simultaneously monitoring radial and transverse growth [67]. The research team attached a square-patterned sensor with high sensitivity (GF = 12.78) to the surface of bamboo, successfully achieving continuous 14-day monitoring of micrometer-scale growth deformations in both horizontal girth and vertical height (Fig. 11b). They quantified the growth rate differences across these dimensions, providing precise data support for studying plant growth patterns. In terms of advances in high-precision integration and multi-parameter synchronous monitoring technology, Yang et al. developed a fully organic, transparent plant electronic skin that overcomes the limitations of traditional monitoring technologies [114]. This ultrathin (approximately 4.5 μm), highly transparent (light transmittance > 85%) sensor enables continuous monitoring over several days without interfering with plant photosynthesis (Fig. 11c). The study not only successfully captured the diurnal growth rhythms of *Brassica rapa* leaves but also applied the sensor to monitor growth responses under abiotic stress conditions, providing an essential tool for understanding plant physiology and ecology. Oh et al. employed patterned transfer printing technology to achieve simultaneous acquisition of strain and temperature signals [115]. The study designed sensor arrays based on different material combinations: an AgNWs/ITO structure was used for high-sensitivity growth strain monitoring, while an AgNWs/PEDOT:PSS/ITO structure enabled strain-insensitive temperature sensing. This multifunctional integration successfully facilitated real-time synchronous monitoring of onion stem growth rate (approximately 3.8 mm day^{-1}) and dynamic changes in leaf surface temperature.

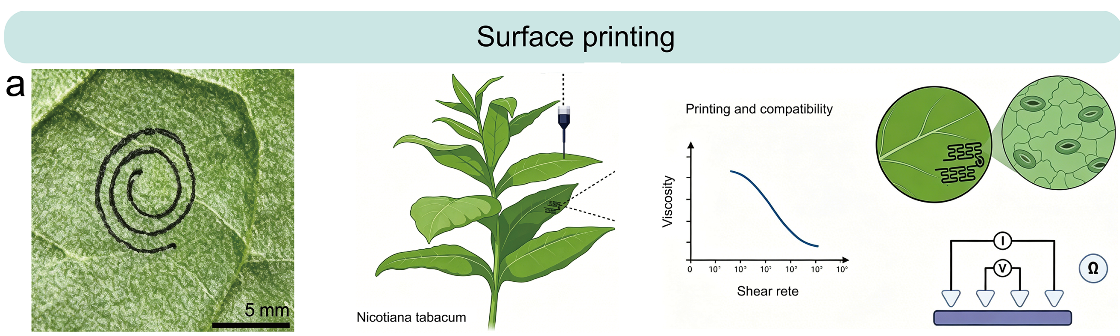

Figure 11: (Continued)

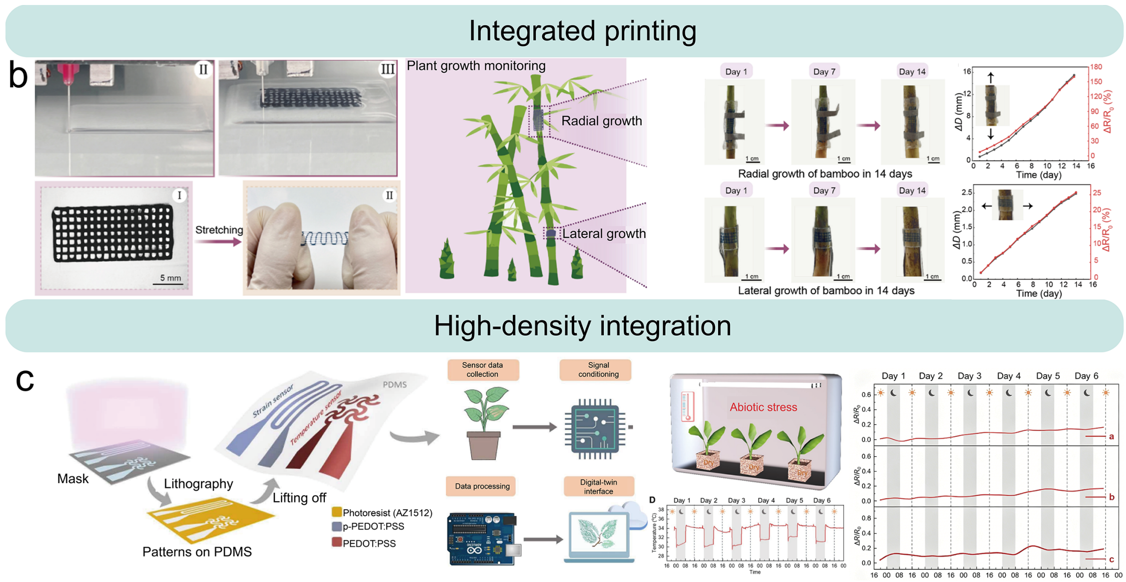

Figure 11: Plant growth monitoring applications of PEDOT:PSS hydrogel sensors. (**a**) High-sensitivity strain sensor based on fully 3D-printed adaptive hydrogel enables long-term precise quantitative monitoring of bamboo growth in both lateral and longitudinal dimensions. Reprinted/adapted with permission from reference [67]. Copyright 2025, copyright OAE Publications. (**b**) Non-invasive monitoring system using fully organic transparent electronic skin allows continuous tracking of plant phenotypic dynamics and stress response processes under environmental challenges. Reprinted/adapted with permission from reference [114]. Copyright 2024, copyright AAAS Publications. (**c**) Direct-write printing for plant surface monitoring. Schematic of DIW printing of shear-thinning conductive ink onto *Nicotiana tabacum* leaf for non-invasive health monitoring. Reprinted/adapted with permission from reference [35]. Copyright 2025, copyright ACS Publications.

Overall, PEDOT:PSS hydrogel strain sensors have demonstrated significant application potential in the field of plant growth monitoring. A quantitative comparison of the plant growth rates reported in different studies reveals that such sensors enable precise monitoring of various plant species (e.g., bamboo, *Brassica rapa*, green onion) across different dimensions (longitudinal, transverse, leaf elongation). The measured growth rates are approximately 1 mm day^{-1} longitudinally and 0.18 mm day^{-1} transversely for bamboo, approximately 0.17 fold day^{-1} for leaf elongation in *Brassica rapa*, and approximately 3.8 mm day^{-1} for vertical growth in green onion. These results indicate that PEDOT:PSS-based strain sensors not only possess high sensitivity and favorable biocompatibility but also can adapt to the dynamic growth characteristics of different plant systems, enabling long-term, continuous, and non-destructive quantitative monitoring.

5.4 Soft Robotics

The development of soft robotics is advancing toward integration, intelligence, and environmental adaptability. PEDOT:PSS hydrogel strain sensors, owing to their biomimetic mechanical properties, tunable conductivity, and excellent compatibility with flexible systems, are emerging as key materials for enabling self-sensing capabilities in soft robots [116–118]. In terms of environmental adaptability applications, researchers have successfully integrated such sensors into soft robotic systems designed for diverse operational environments. For instance, Zhang et al. developed an anisotropic-structured PEDOT:PSS-PVA hydrogel, which was applied to underwater robots due to its outstanding fatigue resistance [32]. This enabled real-time monitoring of tail oscillation patterns and motion state recognition, providing a reliable sensing solution for underwater exploration and environmental monitoring (Fig. 12a). Meanwhile, Xue et al.

combined PEDOT:PSS with functionalized MXene to create a light-responsive hydrogel capable of both actuation and self-sensing [119]. This allows soft robots to perform complex deformations under near-infrared light control while simultaneously monitoring their own states, offering an innovative material platform for closed-loop control in light-driven soft robotics (Fig. 12b).

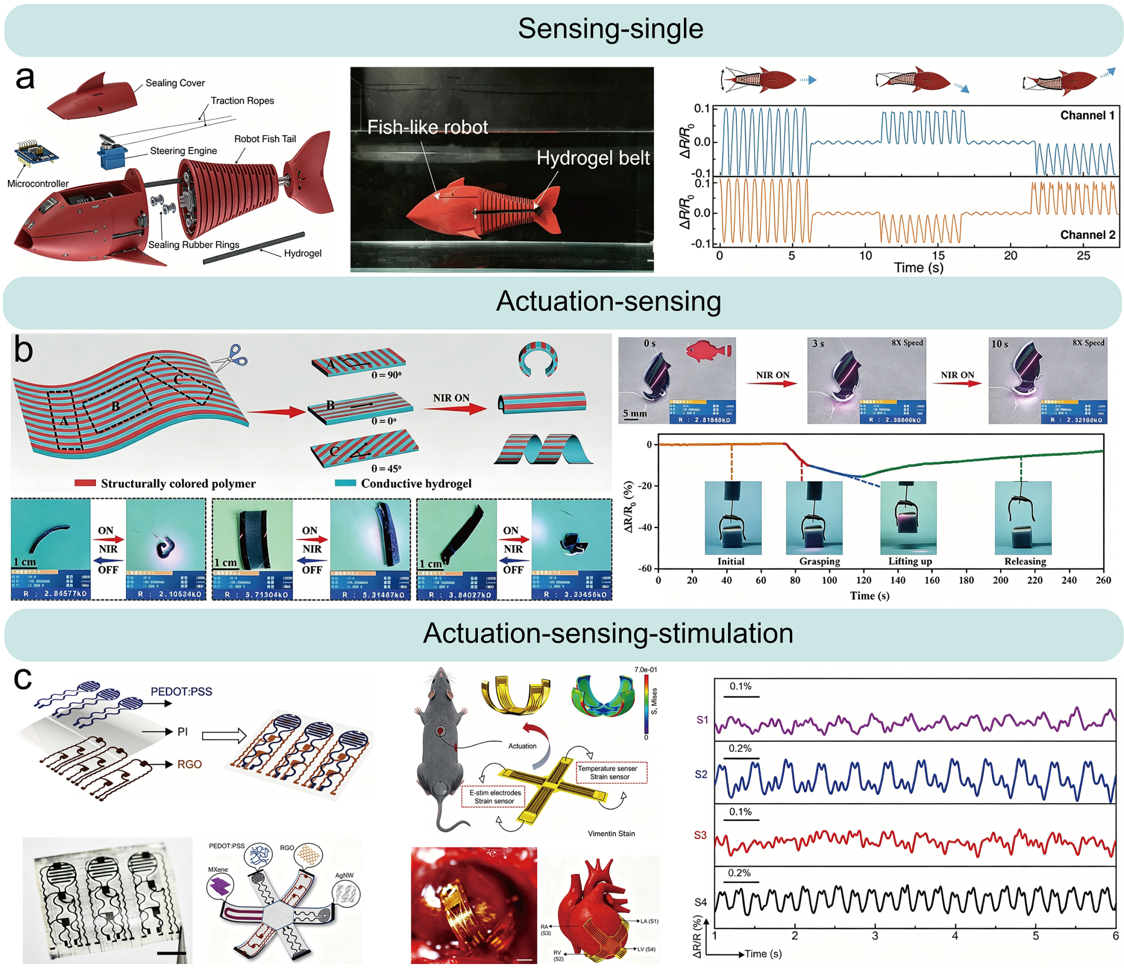

Figure 12: Soft robotics applications of PEDOT:PSS hydrogel sensors. (**a**) Bionic fish soft robot based on fatigue-resistant hydrogel strain sensing achieves underwater autonomous propulsion with real-time dual-channel mechanical signal monitoring and control. Reprinted/adapted with permission from reference [32]. Copyright 2023, copyright Wiley. (**b**) Light-driven soft robot integrated with MXene/PEDOT:PSS highly conductive hydrogel responds to near-infrared light to perform multimodal biomimetic motions such as grasping and rolling. Reprinted/adapted with permission from reference [119]. Copyright 2023, copyright Wiley. (**c**) Implantable electronic skin sensor using multilayer flexible materials simulates biological perception functions to enable long-term stable monitoring of subtle internal strains. Reprinted/adapted with permission from reference [34]. Copyright 2024, copyright Nature.

In the field of medical healthcare, the application of such sensors is propelling implantable robots toward greater intelligence. The study by Zhang et al. demonstrated the multifunctional integration of a PEDOT:PSS-based sensing system in implantable medical soft robots [34]. By integrating strain, chemical, and electrophysiological sensing units into an electronic skin, this research constructed various soft robotic prototypes tailored for different organs, fully illustrating the application potential of PEDOT:PSS in the biomedical field: Vascular monitoring robots integrate strain sensors into a twistable soft cuff, enabling adaptive wrapping around blood vessels and real-time monitoring of blood pressure fluctuations; ingestible gastric robots incorporate a PEDOT:PSS-based pH sensor and a drug delivery module, allowing self-expansion within the stomach to prolong retention time, thereby achieving dual functions of pH monitoring and on-demand drug delivery; epicardial therapeutic robots integrate strain sensors, temperature sensors, and electrical stimulation electrodes, enabling gentle envelopment of the beating heart, real-time monitoring of myocardial contractility, local strain, and temperature changes, while providing on-demand electrical stimulation. Through real-time monitoring of physiological parameters and therapeutic feedback, the above studies have achieved a transition of implantable robots from single-function sensing to an integrated "monitoring-diagnosis-therapy" platform, opening new technological pathways for precision medicine and personalized treatment (Fig. 12c).

Overall, PEDOT:PSS hydrogel strain sensors have successfully enabled self-sensing and closed-loop control functionalities in soft robots through the deep integration of the piezoresistive effect with flexible actuation systems. Specifically, the sensor monitors the deformation of the actuator in real time and converts it into a resistance signal; after processing, this signal is fed back to the actuation unit to dynamically adjust the driving input, thereby forming a "sensing-feedback-actuation" closed-loop circuit. This mechanism allows soft robots to adaptively regulate their movements according to their own state and environmental changes, significantly enhancing operational precision and environmental adaptability.

6 Conclusions and Outlook

This review systematically summarizes the core strategies for enhancing the mechanical properties of PEDOT:PSS hydrogel strain sensors. Through microstructural network design, dynamic crosslinking modulation, and micro-nano engineering, both the mechanical performance and self-healing capability of the sensors have been significantly improved. The synergistic design spanning from micro to macro scales marks the entry of this field into a new stage of multifunctional collaborative optimization, laying a solid foundation for high-precision and reliable monitoring applications.

Looking ahead, although significant progress has been made in optimizing individual properties of PEDOT:PSS hydrogel strain sensors, numerous challenges remain in areas such as multi-property synergy, environmental adaptability, signal processing, and application expansion. Future research can focus on breakthroughs in the following four directions:

Synergistic breakthrough in high sensitivity, wide strain range, and linearity. The trade-off among these three parameters remains a core scientific challenge. High sensitivity typically relies on easily disrupted structures such as microcracks, but the linear response range is often limited to small strain intervals; conversely, achieving a wide strain range often comes at the cost of sensitivity. How to achieve synergistic optimization of these three properties is a critical issue that urgently needs to be addressed in this field.

Synergistic integration of multiple properties. A single hydrogel system must simultaneously meet multiple application requirements: good tissue/substrate adhesion ensures the stability of signal acquisition; self-healing capability extends the service life of the device; and excellent water retention guarantees stable performance during long-term use. Future efforts should focus on achieving the unification of multiple properties through multifunctional crosslinking network design and water molecule regulation strategies.

Signal acquisition and intelligent feedback. Current research primarily focuses on optimizing the sensor itself, with relatively insufficient attention paid to signal processing, feature extraction, and intelligent feedback. How to extract effective information from complex, multimodal sensing signals and achieve closed-loop control with actuators is key to advancing this technology toward practical applications.

Scalability and commercialization are key to advancing this technology toward practical applications. Scalable fabrication capability serves as the fundamental foundation for commercial expansion-only by establishing stable, efficient, and reproducible manufacturing processes can the core market demands for sensor production capacity, consistency, and cost control be met. In turn, the expansion of commercial applications provides continuous impetus for the advancement of scalable technologies, as the diversification of market demands and the continuous extension of application scenarios drive the iterative upgrading of fabrication processes toward higher precision, broader adaptability, and lower cost.

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