

Perspective

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Engineering hydrogel-based conformal epidermal electrodes for human-machine interaction

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Abstract

Hydrogels, with their skin-like physicochemical properties, offer great potential as flexible electrodes for electrophysiological interfaces and high-quality biosignal acquisition in human-machine interaction systems. However, traditional hydrogel electrodes often face issues such as mechanical mismatch with skin, low electrical conductivity, and poor adhesion, which hinder stable biosignal acquisition with high signal-to-noise ratio. To address these challenges, optimizing conductivity, compliance, and adhesion is crucial. This perspective reviews recent advancements in hydrogel electrode optimization, materials design, interface engineering, human-machine interaction applications, and future directions for hydrogel-based biointerfaces.

Keywords: Flexible hydrogel electrodes, human-machine interaction, flexible and wearable epidermal sensor, hydrogel sensor



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INTRODUCTION

With the rapid advance of flexible electronics, wearable sensors that form high-performance interfaces with human skin are gradually replacing conventional rigid devices and have become indispensable in health monitoring^[1-3], active rehabilitation^[4,5], and intelligent human-machine interaction (HMI)^[6-8]. Among the various soft electronic materials under development, hydrogels stand out because their physicochemical characteristics closely resemble those of human skin^[9-14]. When used as epidermal electrodes, hydrogel devices can record diverse biosignals - such as electroencephalograms (EEG) and surface electromyograms (sEMG) - and supply them as high-value inputs to HMI systems^[15,16].

High-performance HMI platforms rely on electrophysiological signals with a high signal-to-noise ratio (SNR)^[17]. Achieving such quality depends on a low-impedance hydrogel-skin interface that minimizes signal attenuation and external interference^[18]. Excellent electrical conductivity of hydrogel electrodes is demanded to support efficient signal transmission. Simultaneously, sufficient mechanical flexibility is required to conform intimately to the microtopography of the skin^[19]. Moreover, strong adhesive properties are necessary to prevent electrode displacement during movement and enable stable and continuous biosignal monitoring [Figure 1A]^[20]. However, conventional hydrogels often suffer from poor conductivity, weak adhesion, and mechanical mismatch with skin, compromising signal quality^[19]. Therefore, next-generation hydrogel electrodes must be engineered with conductive additives, ions, adhesion enhancers, and multidimensional structural optimizations to ensure long-term, stable collection of high-quality physiological data for advanced HMI applications.

PERFORMANCE OPTIMIZATION STRATEGIES AND INTERFACE ENGINEERING OF HYDROGEL ELECTRODES

The three-dimensional network of hydrogels offers intrinsic porosity for incorporating functional fillers, enabling optimization of conductivity, adhesion, and mechanical compliance to enhance skin-electrode interfaces^[21,22]. Common strategies include adding fillers such as tannic acid (TA) and MXene, which improve both conductivity and adhesion, ensuring a low-impedance and stable skin-electrode interface^[23]. For example, Wan *et al.* integrated MXene nanosheets into a self-healing hydrogel made of TA-phenylboronic acid-grafted hyaluronic acid (HA-PBA) [Figure 1B]^[24], resulting in a stable skin interface that supports multimodal biosignal acquisition and additional functions such as ultraviolet (UV) protection and photothermal therapy via MXene's photothermal conversion ability. Furthermore, Wu *et al.* introduced TA into a polyacrylamide (PAM) hydrogel and immersed it in sodium chloride (NaCl) solution, enhancing ionic conductivity and enabling high-performance signal acquisition from hairy skin surfaces [Figure 1C]^[17]. In addition to TA, polydopamine (PDA) is also a commonly used functional filler to improve the adhesive and mechanical properties of hydrogel electrodes. For example, Han *et al.* added PDA nanoparticles to a polyvinyl alcohol (PVA)/polyvinylpyrrolidone (PVP) hydrogel [Figure 1D], improving adhesion and enabling stable attachment to various surfaces, including skin, metal, and glass [Figure 1E]^[19]. This electrode showed low interface impedance, ensuring stable EEG signal acquisition [Figure 1F]. PDA and TA enhance adhesion through hydrogen bonds and π - π interactions with skin proteins, improving interfacial stability during movement^[17,19]. Liquid metal is another filler that boosts conductivity and flexibility, making hydrogels suitable for dynamic, stretchable applications^[1]. Hu *et al.* incorporated liquid metal into a dual-network hydrogel of PAM and gelatin, achieving high conductivity and intelligent adhesiveness [Figure 1G]^[25], resulting in superior sEMG signal acquisition compared to commercial electrodes. This hydrogel maintained stable signal acquisition for up to 48 h, showing promise for wearable bioelectronics [Figure 1H].

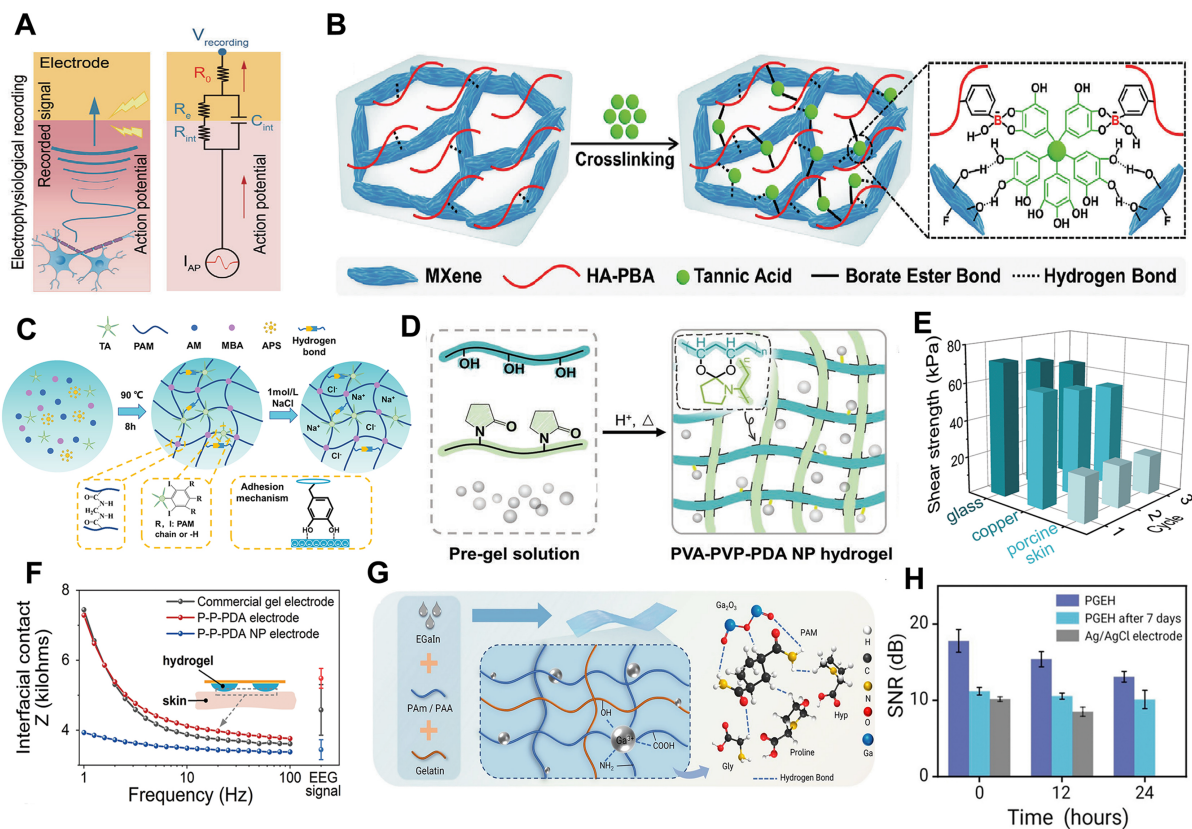


Figure 1. (A) Schematic illustration of a high-performance hydrogel-skin interface^[20]. Reprinted with permission. Copyright 2025, John Wiley & Sons; (B) Fabrication schematic of MXene-HA-PBA-TA-PAM hydrogel. Reprinted with permission^[24]. Copyright 2024, John Wiley & Sons; (C) Preparation process of TA-NaCl-PAM hydrogel. Reprinted with permission^[17]. Copyright 2023, John Wiley & Sons; (D) Schematic illustration of PVA-PVP-PDA NP hydrogel preparation. Reprinted with permission^[19]. Copyright 2023, John Wiley & Sons; (E) Repeatable adhesion behavior of the PVA-PVP-PDA NP hydrogel on porcine skin, copper, and glass surfaces^[19]. Reprinted with permission. Copyright 2023, John Wiley & Sons; (F) Interfacial impedance comparison among commercial gel electrodes, PVA-PVP-PDA hydrogel electrodes, and PDA NP-loaded PVA-PVP hydrogels over 1–100 Hz^[19]. Reprinted with permission. Copyright 2023, John Wiley & Sons; (G) Schematic of the preparation process for the PGEH^[25]. Reprinted with permission. Copyright 2025, Springer Nature; (H) Comparison of SNR among the three electrodes during long-term EMG monitoring^[25]. Reprinted with permission. Copyright 2025, Springer Nature. HA-PBA: Phenylboronic acid-grafted hyaluronic acid; TA: tannic acid; PAM: polyacrylamide; PVA: polyvinyl alcohol; PVP: polyvinylpyrrolidone; PDA: polydopamine; NP: nanoparticle; PGEH: polyacrylamide/gelatin/EGaIn hydrogel; SNR: signal-to-noise ratio; EMG: electromyograms; EEG: electroencephalograms; AM: acrylamide; MBA: N,N'-methylenebisacrylamide; APS: ammonium persulfate.

Table 1 summarizes key performance metrics and applications of these optimized hydrogel electrodes, highlighting their potential for future interface engineering and multifunctional integration, with higher SNR than commercial electrodes.

DEVELOPMENT AND APPLICATION OF INTELLIGENT HMI SYSTEMS BASED ON HYDROGEL ELECTRODES

Optimized hydrogel electrodes enable low-impedance skin-electrode interfaces, facilitating the acquisition of high SNR physiological signals, making them ideal for various HMI applications. These electrodes are integrated into signal acquisition systems and combined with neural networks for real-time signal classification, supporting applications such as sign language recognition, active rehabilitation, attention monitoring, and remote health management.

Table 1. Summary of performance and applications of hydrogel electrodes in recent studies

Materials	Conductivity (S·m ⁻¹)	Adhesiveness (kPa)	Stretchability (strain)	Modulus (kPa)	SNR (dB)	Application
CMC-PDA-PEDOT:PSS-PA hydrogel ^[26]	0.08	6	400%	100	30 vs. 30 ^{a)}	sEMG
PVA-PEI-CaCl ₂ hydrogel ^[27]	0.6	10	1,400%	15	8.5 vs. 6.3	sEMG, EEG
AgNPs/MXene/GG/Alg-PBA ^[23]	0.005	NA ^{b)}	250%	NA ^{b)}	16 vs. 10 ^{a)}	sEMG, ECG
fCNT/TA/PVA/PAA ^[28]	40	49	1,000%	100	NA ^{b)}	sEMG
AgNW hydrogel ^[29]	1	NA ^{b)}	200%	NA ^{b)}	NA ^{b)}	sEMG
SOH hydrogel ^[30]	0.8	NA ^{b)}	250%	NA ^{b)}	30 vs. 30 ^{a)}	sEMG
PVA-PVP-PEDOT:PSS hydrogel ^[31]	0.6	NA ^{b)}	150%	8	15 vs. 9 ^{a)}	sEMG, ECG
AgNPs/MXene/GG/Alg-PBA hydrogel ^[32]	0.02	19	200%	2,000	17.5	ECG
DAT ^[33]	0.8	19	1,200%	20	21 vs. 15 ^{a)}	sEMG

^{a)}Commercial gel Ag/AgCl electrodes or standard wet Ag/AgCl electrodes; ^{b)}NA: Not reported in the literature. sEMG: Surface electromyograms; EEG: electroencephalograms; TA: tannic acid; PVA: polyvinyl alcohol; PBA: phenylboronic acid; PVP: polyvinylpyrrolidone.

For example, Wu *et al.* developed a dual-modality sensing platform using sEMG hydrogel electrodes and foam-based pressure sensors, enabling real-time hand gesture classification and driving a rehabilitation glove for stroke patients [Figure 2A]^[17]. Xie *et al.* designed hydrogel electrodes with antibacterial properties, which, when integrated into a dual-channel sEMG system, enabled real-time prosthetic hand control through AI-based recognition [Figure 2B]^[34]. Gao *et al.* used Ag nanowire-modified hydrogel electrodes in a stretchable throat patch, combined with an accelerometer, to classify vocalization and swallowing, supporting remote monitoring and rehabilitation [Figure 2C]^[29]. Han *et al.* incorporated high-adhesion hydrogel electrodes into EEG acquisition circuits for real-time attention state classification, demonstrating potential for brain-machine interfaces [Figure 2D]^[19]. Wan *et al.* used MXene-modified hydrogel electrodes to collect sEMG signals for sign language translation, enabling communication between hearing-impaired individuals and the public [Figure 2E]^[24].

CHALLENGE AND PERSPECTIVES

Despite significant advances in hydrogel electrode materials and device integration for HMI applications, several challenges hinder their large-scale and long-term deployment:

First, Hydrogel electrodes are prone to dehydration due to temperature and humidity fluctuations, which reduces conductivity and increases impedance, compromising signal stability. While strategies such as hydrogen bonding networks and glycerol incorporation help with water retention, achieving week-long stability without losing flexibility or conductivity remains a challenge^[35]. Optimizing the crosslinking method to enhance the hydrogel's three-dimensional network could improve water absorption and dehydration resistance. Additionally, mechanical deformation and contamination can damage the hydrogel, further degrading signal quality and device lifespan.

Second, Most hydrogel electrodes target a single electrophysiological signal (e.g., sEMG), requiring additional sensors for multimodal HMI, thus increasing size, cost, and complexity^[36]. Advances in multimodal epidermal sensors, circuit design, and data fusion algorithms could allow hydrogel electrodes to measure multiple signals (e.g., sEMG, strain, pressure, or temperature) simultaneously on the same



Figure 2. (A) Real-time active rehabilitation system based on dual-modality sensing of muscle force and sEMG^[17]. Reprinted with permission. Copyright 2023, John Wiley & Sons; (B) Antibacterial hydrogel electrodes for prosthetic control in HMI applications: B₁ System operation schematic; B₂ Real-time prosthetic hand control via dual-channel sEMG signals^[34]. Reprinted with permission. Copyright 2025, American Chemical Society; (C) Throat motion monitoring and rehabilitation using sEMG and accelerometer-based dual-modality sensing: C₁ Cloud-based interface for real-time throat motion tracking; C₂ Classification accuracy of 13 throat movements from two subjects^[29]. Reprinted with permission. Copyright 2023, Springer Nature; (D) Continuous attention level assessment system: D₁ Schematic of wireless EEG acquisition system; D₂ Confusion matrix of attention classification results; D₃ Real-time system interface for sustained attention evaluation^[19]. Reprinted with permission. Copyright 2023, John Wiley & Sons; (E) Machine learning-assisted sign language recognition based on sEMG: E₁ CNN-based algorithm framework for sign language translation; E₂ Post-training accuracy/loss curves and confusion matrix for eight sign gestures^[24]. Reprinted with permission. Copyright 2024, John Wiley & Sons. HMI: Human-machine interaction; sEMG: surface electromyograms; EEG: electroencephalograms; CNN: convolutional neural network.

platform. Innovations in structural and circuit design can enable integrated physiological signal sensing.

Next, electromagnetic interference (EMI) can disrupt signal acquisition, especially at high frequencies, affecting signal stability and the SNR^[37-40]. Hydrogel electrodes must have sufficient EMI resistance. Using liquid metal for EMI shielding is common, but its efficiency needs improvement in specific frequency ranges^[41]. Designing gradient or porous structures could enhance shielding in targeted directions or achieve absorption-based shielding.

Finally, due to their excellent biocompatibility, hydrogel electrodes hold great potential for human rehabilitation applications. In future research, they could serve as interface materials for brain-computer interfaces, sensing brain electrical signals to enable human control of external machinery, thus helping patients who are unable to move independently regain mobility.

DECLARATIONS

Authors' contributions

Xiao, M., Zhang, X., and Luo, Y. contributed equally to this work.

Wrote the original draft: Xiao, M.; Zhang, X.; Luo, Y.

Supervised, reviewed, and revised the manuscript: Xie, R.; Tao, K.; Wu, J.

Availability of data and materials

Not applicable.

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Conflicts of interest

Wu, J. is a Guest Editor of the journal *Soft Science*. Wu, J. was not involved in any steps of editorial processing, notably including reviewers' selection, manuscript handling and decision making. The other authors declare that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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