

Bioinspired adhesive and self-healing ionotronic hydrogel for tactile sensing and human–machine interaction

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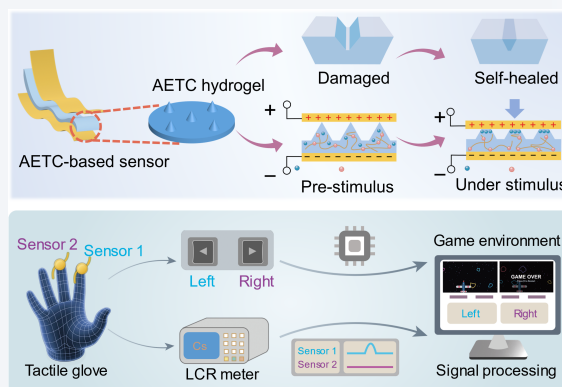
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ABSTRACT: The development of ionotronic hydrogels that can transmit electrical signals and withstand mechanical deformation holds great promise for applications in soft electronics and human–machine interfaces. However, their operational durability is often compromised by mechanical damage, such as cracks and punctures. Herein, we report a sea cucumber-inspired ionotronic hydrogel that features room-temperature self-healing capability and interfacial capacitive sensing. Reversible ionic electrostatic interactions and dynamic hydrogen-bonding networks impart effective self-healing, whereas pressure-induced interfacial contact evolution coupled with electrical-double-layer formation and ionic modulation at the hydrogel-electrode interface enables sensitive capacitive signal transduction. The obtained hydrogel exhibits stretchability exceeding 1000%, high ionic conductivity ($> 0.49 \text{ S} \cdot \text{m}^{-1}$), and strong adhesion and effective self-healing capability. In addition, we demonstrate that the hydrogel-based ionotronic sensor achieves a high sensitivity ($\sim 20.6 \text{ kPa}^{-1}$), a wide detection range of up to $\sim 1 \text{ MPa}$, rapid response/recovery time of $\sim 30/40 \text{ ms}$, and excellent stability under various mechanical loading conditions. As a proof of concept, a hydrogel-based tactile sensing glove achieves real-time, robust tactile sensing, shape recognition, and directional-intent decoding, allowing reliable human–machine interaction control. This work provides a simple strategy for developing adhesive, self-healing ionotronic platforms for wearable sensing and human–machine interaction.

KEYWORDS: ionotronic hydrogel, adhesion, self-healing, tactile sensing, human–machine interaction



1 Introduction

Soft materials that integrate high electrical conductivity with tissue-like flexibility are essential for the advancement of soft sensors [1], soft robotics [2], stretchable electronics [3], and stretchable displays [4]. Hydrogels are widely regarded as promising materials for soft electronics, as their mechanical properties closely resemble those of various biological tissues [5, 6]. Recent studies have emphasized

several key characteristics of hydrogels, including high fracture toughness [7], high stretchability, tissue-like Young's modulus [8, 9], ionic conductivity [10], and biocompatibility [11]. These attributes make hydrogels particularly suitable for applications in bioelectronics, soft robotics, and wearable electronics [12]. The elasticity of hydrogels arises from the reversible conformational adjustments of the polymer chains at the cross-link sites [13]. However, hydrogels with excellent stretchability often suffer from mechanical instability during repeated deformation, as the relaxation of dangling polymer chains or irreversible rupture of chemical bonds leads to energy dissipation, structural damage, and ultimately compromised resilience [14, 15]. This inherent vulnerability to mechanical damage limits their long-term reliability and hinders widespread adoption in durable applications [16]. Consequently, the development of self-healing hydrogels that can

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recover from mechanical damage and restore their original properties under ambient conditions is essential for advancing the next generation of resilient soft electronics.

In recent years, extensive research has focused on developing stretchable self-healing materials that restore their structure and properties after damage [17]. Current approaches can be broadly classified into extrinsic self-healing through the encapsulation of healing agents and intrinsic self-healing via noncovalent supramolecular interactions such as hydrogen bonding [18, 19], ionic interactions [20], metal ion coordination [21], and van der Waals forces [22], or dynamic covalent bonds such as disulfide bonds [23], and Diels–Alder reactions [24]. However, achieving a hydrogel system that simultaneously integrates high stretchability, low mechanical hysteresis, effective self-healing under ambient conditions, and stable ionic conductivity remains a fundamental challenge. Strong interactions improve toughness but slow chain diffusion and increase hysteresis, compromising fast recovery. Nature offers an ingenious solution to address this trade-off. Certain biological systems, such as the proteins found in cephalopod suckers, exhibit self-healing properties under ambient conditions through a segmented, semicrystalline structure composed of both amorphous and crystalline domains (β -sheets) [17, 25–27]. This distinctive architecture endows cephalopod sucker proteins with exceptional self-healing properties in both ambient and aquatic environments due to the presence of a semicrystalline morphology, numerous hydrogen bonds, and hydrophobic groups.

Herein, we present a sea cucumber-inspired ionotronic hydrogel that integrates intrinsic adhesion, room-temperature self-healing, and interfacial capacitive sensing. Reversible ionic interactions and dynamic hydrogen bonds enable effective self-healing and strong adhesion, while pressure-dependent interfacial contact evolution together with electrical-double-layer (EDL) effects at the hydrogel-electrode interface enables sensitive capacitive signal transduction. The hydrogel exhibits exceptional stretchability ($> 1000\%$), a high ionic conductivity ($> 0.49 \text{ S}\cdot\text{m}^{-1}$), and excellent adhesion and effective self-healing behavior. Furthermore, we fabricate ionotronic sensors by placing the microstructured hydrogel between two copper (Cu) electrodes. The resulting ionotronic sensor demonstrates a high sensitivity ($\sim 20.6 \text{ kPa}^{-1}$), a wide detection range ($\sim 1 \text{ MPa}$), a fast response/recovery time ($\sim 30 \text{ ms}/\sim 40 \text{ ms}$), and exceptional stability under various mechanical loading conditions. As a proof of concept, a smart tactile glove integrating the hydrogel-based sensor demonstrates real-time tactile sensing, shape recognition, and directional-intent decoding for reliable human–machine interaction control. This work demonstrates a promising strategy for the design of next-generation smart monitoring electronics for human–machine interaction and wearable applications.

2 Results and discussion

2.1 Bioinspired design and working mechanism of the AETC hydrogel

Echinoderms such as sea cucumbers exemplify biologically damage-tolerant and mechanically robust organisms, whose body walls are enriched in polypeptide chains bearing numerous hydrogen-bond donors and acceptors that can reversibly form and break hydrogen bonds (Fig. 1(a)) [28, 29]. This hierarchical architecture provides inspiration for effective self-healing under ambient conditions.

When damage occurs, some of the reversible noncovalent interactions are temporarily interrupted; however, the rapid reformation of the hydrogen-bond network restores the material's structural integrity and maintains ionic transport pathways relevant to bioelectrical signaling (Fig. 1(b)) [17, 30]. In parallel, bioelectrical signaling in living organisms is predominantly mediated by ionic conduction. Upon external mechanical stimulation, directional ion transport across cell membranes, governed by ion channels and pumps, enables precise control of ionic flux and underpins complex information processing in the nervous system. The resulting electrical signals rapidly propagate along neuronal pathways, thereby enabling organisms to perceive external stimuli, such as touch, temperature variations, and chemical cues (Fig. 1(c)) [27, 31, 32].

Inspired by the hydrogen-bond donors and acceptors and the ion dynamics of the sea cucumber tissue, we design an AETC hydrogel-based ionotronic system that combines self-healing behavior under ambient conditions with stimulus-responsive ionic signaling observed in echinoderms (Fig. 1(d)). The AETC hydrogel is prepared by polymerizing [2-(acryloyloxy)ethyl]trimethylammonium chloride, whose polymer chains incorporate highly hydrophilic ionic groups and flexible, weakly hydrophobic alkyl segments, while mobile anions serve as charge carriers that enable ionic conduction. In addition, a hydrogen-bond-forming agent, tannic acid (TA), is incorporated to establish dynamic reversible crosslinks, thereby enhancing energy dissipation and adhesion under mechanical deformation [33]. This dynamic hydrogen-bonding network plays a key role in the self-healing behavior of the hydrogel. Notably, electrostatic interactions between the polycationic polymer backbone and mobile anions act synergistically with dynamic hydrogen bonding, thereby enhancing mechanical robustness and self-healing behavior under ambient conditions [34, 35]. As depicted in Fig. 1(e), the synergistic effect of hydrogen bonding and electrostatic interactions between cations and anions enables the hydrogel to exhibit effective self-healing under ambient conditions. Additionally, mechanical loading brings the microstructured AETC hydrogel into contact with the electrode, thereby changing the interfacial contact state and enabling EDL formation together with interfacial ionic modulation at the hydrogel-electrode interface (Fig. 1(f)). Figure 1(g) presents the chemical structures of the ionic monomer [2-(acryloyloxy)ethyl]trimethylammonium chloride ([AETC]Cl), the hydrogen-bonding agent TA, and the photoinitiator I-1173. Under ultraviolet (UV) irradiation, [AETC]Cl polymerizes into a polycationic network that is charge-balanced by mobile anions. Meanwhile, TA forms multiple hydrogen bonds with the polymer chains, yielding a hydrogel that integrates mechanical integrity with efficient ionic conduction (Fig. 1(h) and Figs. S1–S3 in the Electronic Supplementary Material (ESM)). Scanning electron microscopy (SEM) images (Fig. S4 in the ESM) show a homogeneous and uniform surface morphology of the AETC hydrogel film.

2.2 Characterization and properties of the AETC hydrogels

To rationally tailor the properties of the AETC hydrogels, we prepare AETC hydrogels using [2-(acryloyloxy)ethyl]trimethylammonium chloride as the primary monomer, with TA contents of 0.25 wt.%, 0.50 wt.%, 1.00 wt.%, and 1.50 wt.% relative to the total monomer mass, denoted as AETC1, AETC2, AETC3, and AETC4, respectively. With increasing TA contents, the Fourier

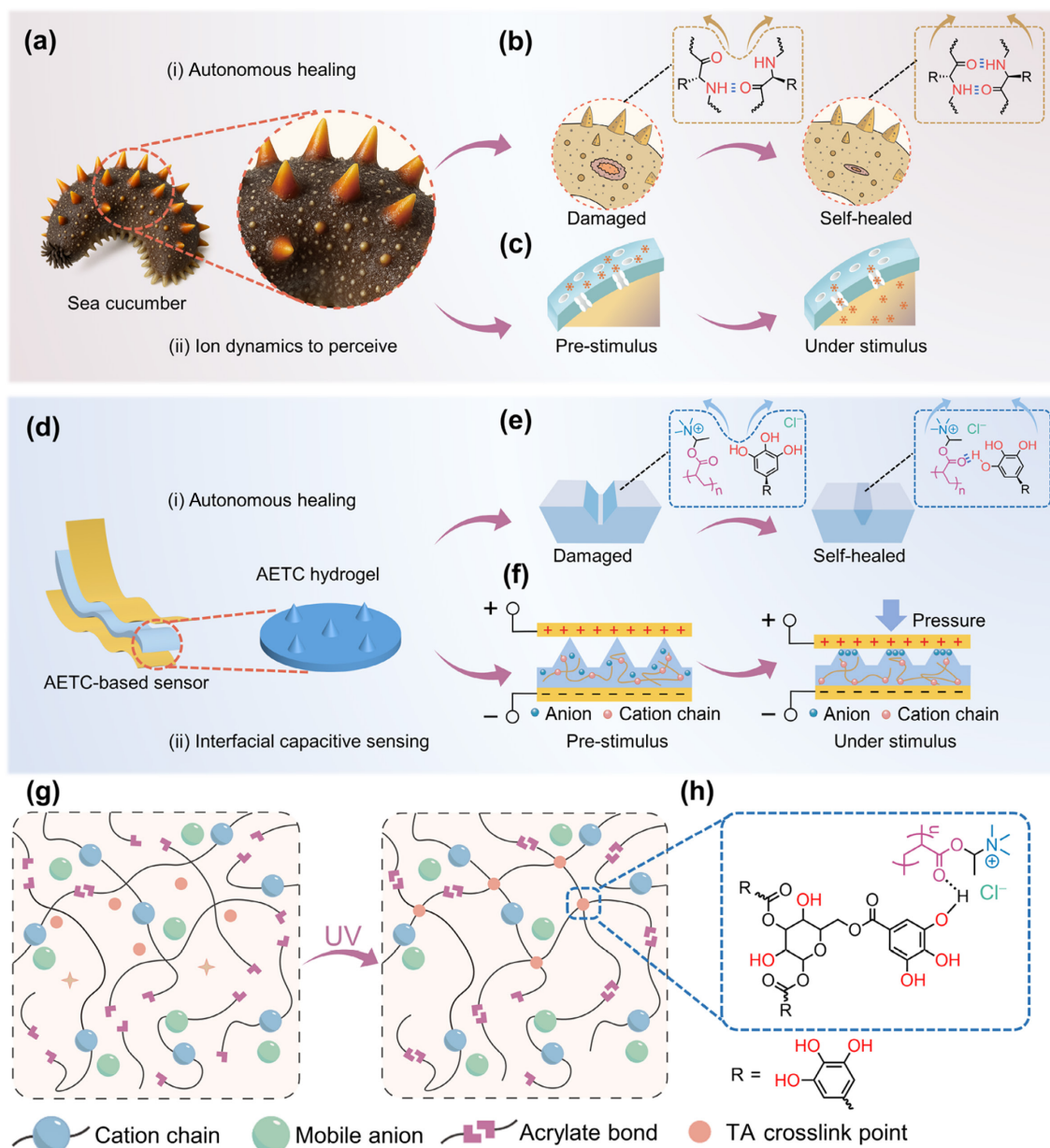


Figure 1 Bioinspired design and working mechanism of the AETC hydrogel. (a) Schematic illustration of sea cucumber-inspired self-healing and ion-dynamic sensing. (b) Self-healing mechanism of the sea cucumber, enabled by reversible hydrogen bonds. (c) Ionic behavior of sea cucumber tissue before and under external mechanical stimulation. (d) Schematic diagram of the AETC-based ionotronic sensor with microstructured AETC hydrogel. (e) Contact-assisted healing mechanism of the AETC hydrogel after complete fracture. (f) Interfacial capacitive sensing inspired by ion dynamics in sea cucumber tissue. (g) Chemical structure of the AETC hydrogel precursor components and the polymer network after UV curing. (h) Chemical structure of the crosslinking point in the AETC hydrogel.

transform infrared (FTIR) spectra of the AETC hydrogels show strengthened hydrogen-bonding interactions within the AETC hydrogel network (Fig. 2(a)). All AETC hydrogels exhibit high transparency in the visible region (Fig. 2(b)). For example, a 1-mm-thick AETC1 hydrogel displays a transmittance of 91.6% at 600 nm, and the inset of Fig. 2(b) shows a photograph of the corresponding hydrogel.

The TA content profoundly affects the mechanical and electrical properties of the AETC hydrogels. The compressive stress-strain curves of the AETC hydrogels are presented in Fig. 2(c), with the corresponding compressive modulus summarized in Fig. S5 in the ESM. With increasing TA contents, the compressive modulus shows a slight increase from 0.16 to 0.20 MPa. In addition, uniaxial

tensile tests are performed (Fig. 2(d)), and the Young's modulus increases from 0.24 to 0.37 MPa as the TA content increases (Fig. 2(e)). The AETC hydrogel displays remarkable uniaxial stretchability exceeding 1000% without relying on permanent chemical cross-linkers (Fig. S6 in the ESM). The maximum fracture strain decreases, whereas the tensile strength increases with increasing TA contents (Fig. 2(f)). The hydrogel also tolerates twisting, bending, stretching, and readily recovers its original shape (Fig. S7 in the ESM). Figure 2(g) presents stress-strain curves measured under uniaxial tensile loading-unloading at maximum strains of 10%, 20%, 50%, and 100%. The observed hysteresis loops are attributed to energy dissipation during the loading-unloading process. The increasing loop area at larger deformations indicates

more pronounced energy dissipation and viscoelastic effects, while the AETC hydrogel still maintains reversible tensile behavior. Under a constant tensile strain of 50%, the AETC hydrogel maintains nearly constant stress over 20,000 s (Fig. 2(h)). The stable mechanical response indicates minimal stress relaxation.

In addition, 90° peel-off tests are performed to evaluate the adhesion energy between the AETC hydrogels and a glass substrate. The interfacial toughness of AETC1 to AETC4 at the hydrogel-glass interface ranges from 143 to 391 J·m⁻² (Fig. 2(i)), indicating progressively enhanced resistance to interfacial debonding. Such robust adhesion helps suppress interfacial slippage between the sensing material and the electrode during operation. Furthermore,

the ionic conductivity is a key parameter governing the performance of ionic conductors. The Nyquist plots of AETC1 to AETC4 are obtained from AC impedance measurements (Fig. 2(j)). A slight decrease in ionic conductivity is observed with increasing TA content, decreasing from 0.82 to 0.49 S·m⁻¹ (Fig. 2(k)). To further evaluate the practical stability of the hydrogel under ambient exposure, long-term mass-change measurements are conducted under ambient conditions. As shown in Fig. S8 in the ESM, the normalized mass of the AETC hydrogel remains almost unchanged over 30 days under fluctuating relative humidity, indicating good water-retention stability. Such stability is beneficial for maintaining polymer-chain mobility, ionic transport, and

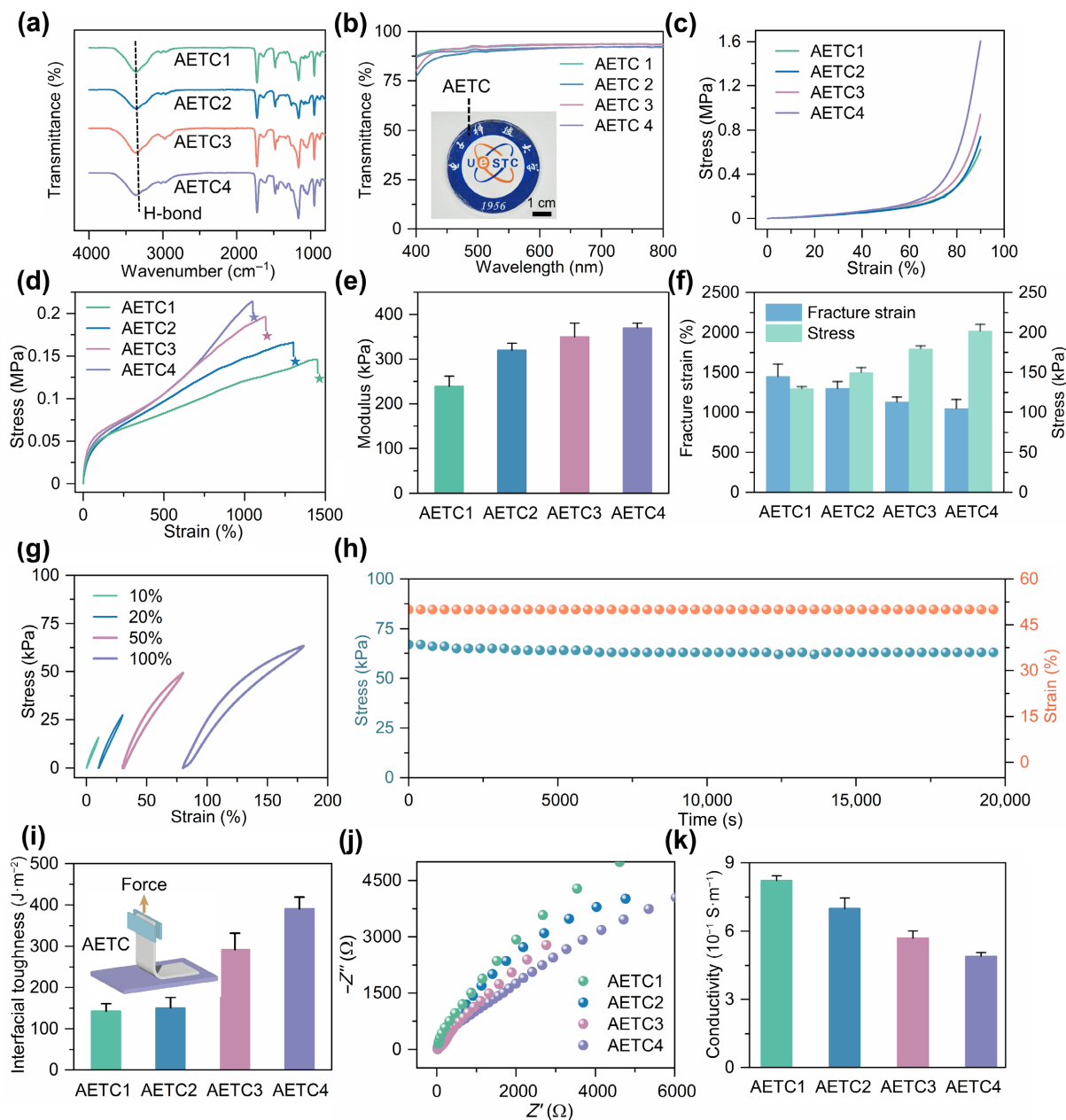


Figure 2 Characterization and properties of the AETC hydrogels. (a) FTIR spectra of AETC1 to AETC4 hydrogels. (b) Transmittance spectra of the AETC1 to AETC4 hydrogels in the visible range (the inset shows a photograph of an AETC hydrogel). (c) Uniaxial compressive stress-strain curves of AETC1 to AETC4 hydrogels. (d) Uniaxial tensile stress-strain curves of AETC1 to AETC4 hydrogels. (e) Young's modulus of AETC1 to AETC4 hydrogels. (f) Fracture strain and strength of AETC1 to AETC4 hydrogels. (g) Uniaxial tensile loading-unloading curves at maximum strains of 10%, 20%, 50%, and 100%. (h) Stress variation of the AETC hydrogel with time under 50% tensile strain. (i) Interfacial toughness of AETC1 to AETC4 hydrogels during the 90° peel-off test (the inset shows a schematic of the 90° peel-off test). (j) Nyquist plots of AETC1 to AETC4 hydrogels. (k) Ionic conductivity of AETC1 to AETC4 hydrogels.

interfacial compliance. Nevertheless, prolonged unprotected exposure may still cause gradual water loss, thereby reducing ionic mobility and potentially degrading sensing performance.

2.3 Adhesive properties and mechanisms of the AETC hydrogel

A commonly employed technique for integrating hydrogels with soft electronics is the “cut-and-attach” approach [33]. Nonetheless, in both the manufacturing and operational stages of the device, an excessive amount of water may cause the hydrogel to detach from the electrode when exposed to even slight shear stress. To mitigate this issue and enhance adhesion, it is essential to investigate the fundamental adhesion mechanisms of the hydrogel, along with the influence of various substrates on its adhesive properties. Figure 3(a) illustrates the adhesion mechanisms and adhesion performance of the AETC hydrogel on different substrates. The adhesion mechanisms involve dipole–dipole interactions, hydrogen bonding, electrostatic interactions, and van der Waals forces. These forces collectively determine the adhesion of the hydrogel to the substrates. Figure 3(b) presents the experimental adhesion results of the hydrogel on different substrates, including glass, plastic, metal, silicone, and plasticine. The results indicate that the AETC hydrogel exhibits stable adhesion on all tested substrates. Such substrate-insensitive adhesion implies the presence of multiple, cooperative interfacial interactions. Beyond interfacial adhesion, bulk tear resistance is further evaluated to probe chain-level debonding and energy dissipation. As shown in Fig. 3(c), dynamic hydrogen bonds are formed between TA molecules and polycationic chains, and reversible debonding under mechanical loading dissipates energy and enhances adhesion. Meanwhile, electrostatic attractions between the polycationic segments and mobile anions provide additional intermolecular binding, thereby strengthening adhesion. During detachment from a clean glass slide, the AETC hydrogel is stretched without fracturing (Fig. 3(d)).

During peeling, interfacial debonding of these reversible interactions forms an interfacial dissipation region, whereas during tearing, analogous debonding events occur within the crack-tip process zone, leading to increased fracture energy [36]. With increasing TA contents from AETC1 to AETC4, the force–displacement curves shift toward higher peak forces, consistent with enhanced energy dissipation enabled by more abundant reversible hydrogen bonds (Fig. 3(e)). Accordingly, the fracture energy increases progressively from 9 to 18 kJ·m^{−2} across AETC1 to AETC4, indicating an overall enhancement in tear toughness (Fig. 3(f)). Figure 3(g) illustrates the deformation and crack propagation of the hydrogel during loading, thereby demonstrating the tear resistance of the AETC hydrogel.

2.4 Self-healing properties and mechanisms of the AETC hydrogel

The evaluation of self-healing capability largely depends on several factors, including the material characteristics and the type of damage (such as scratches [37], punctures [38], cuts [39], and cracks [40]). To establish a more comprehensive evaluation of the AETC hydrogel, we assess its self-healing behavior under different mechanical damage conditions from the perspectives of both structural recovery and functional recovery. In addition to qualitative demonstrations, the healing performance is quantitatively evaluated by comparing the pristine and healed states

in terms of tensile stress–strain behavior, Young’s modulus, post-healing mechanical durability, and electrical recovery after damage. Specifically, the self-healing behavior of the AETC hydrogel is evaluated under both mild and severe mechanical damage conditions, including spontaneous recovery after puncture and contact-assisted healing after complete fracture under ambient conditions.

To evaluate the self-healing performance of the AETC hydrogel, the hydrogel (10 mm × 20 mm × 1 mm) is employed as a conductive interconnect to a light-emitting diode (LED). Figure 4(a) schematically illustrates the LED brightness under different states (original, stretching, cutting, and healed). The LED stays on in the original and stretched states, turns off after cutting, and lights up again after contact-assisted healing, as confirmed by the photographs in Fig. 4(b). These results indicate that the AETC hydrogel sustains electrical conduction under deformation and recovers electrical continuity after contact-assisted healing from cutting damage. In addition, the AETC hydrogel shows robust self-healing and high stretchability. As shown in Fig. S9 in the ESM, the cut AETC hydrogels reconnect after contact-assisted healing, and the healed hydrogel can be stretched to 1000% strain without fracture. To further evaluate the mechanical recovery after damage, tensile stress–strain curves and Young’s modulus values of the initial, puncture-healed, and cut-healed hydrogels are compared (Fig. S10 in the ESM). The Young’s modulus remains almost unchanged after puncture healing, decreasing only slightly from 210 to 205 kPa, while the cut-healed hydrogel retains a modulus of 190 kPa. These results indicate effective restoration of mechanical performance after both puncture and cutting damage. To further evaluate the post-healing mechanical durability of the cut-healed hydrogel, tensile stress–strain curves are recorded after the 5th, 10th, and 20th stretch–release cycles (Fig. S11 in the ESM). The tensile response remains comparable to that of the initial hydrogel after the 5th and 10th cycles, whereas a slight decrease in stress is observed after the 20th cycle. Nevertheless, the cut-healed hydrogel still maintains substantial load-bearing capability, indicating good mechanical durability after repeated deformation of the healed hydrogel.

To elucidate the mechanism underlying the healing behavior of the AETC hydrogel, the recovery process is attributed to reversible noncovalent interactions within the polymer network, including dynamic ionic interactions and hydrogen bonding (Fig. S12 in the ESM). When the material is damaged, the original ionic pairs and hydrogen bonds are disrupted, leading to the temporary loss of structural integrity. However, owing to the retained water within the polymer network, the polymer chains remain mobile and can diffuse across the damaged interface, allowing dissociated ions and polar groups to reassociate through dynamic ionic and hydrogen-bonding interactions. For puncture damage, the damaged region remains spatially continuous after withdrawal of the needle, allowing spontaneous recovery under ambient conditions without manual reassembly. By contrast, for complete fracture, recontact of the separated interfaces is necessary before interfacial diffusion and dynamic rebonding can occur. Such reconstruction gradually rebuilds the physical crosslinking network, thereby restoring cohesion and mechanical integrity without external stimuli (Fig. 4(c)).

Additionally, our AETC hydrogel (1 mm thick) is resistant to needle puncture (needle-tip radius 0.24 mm) (Fig. 4(d)). Electrical recovery of the AETC hydrogel is quantified by monitoring the

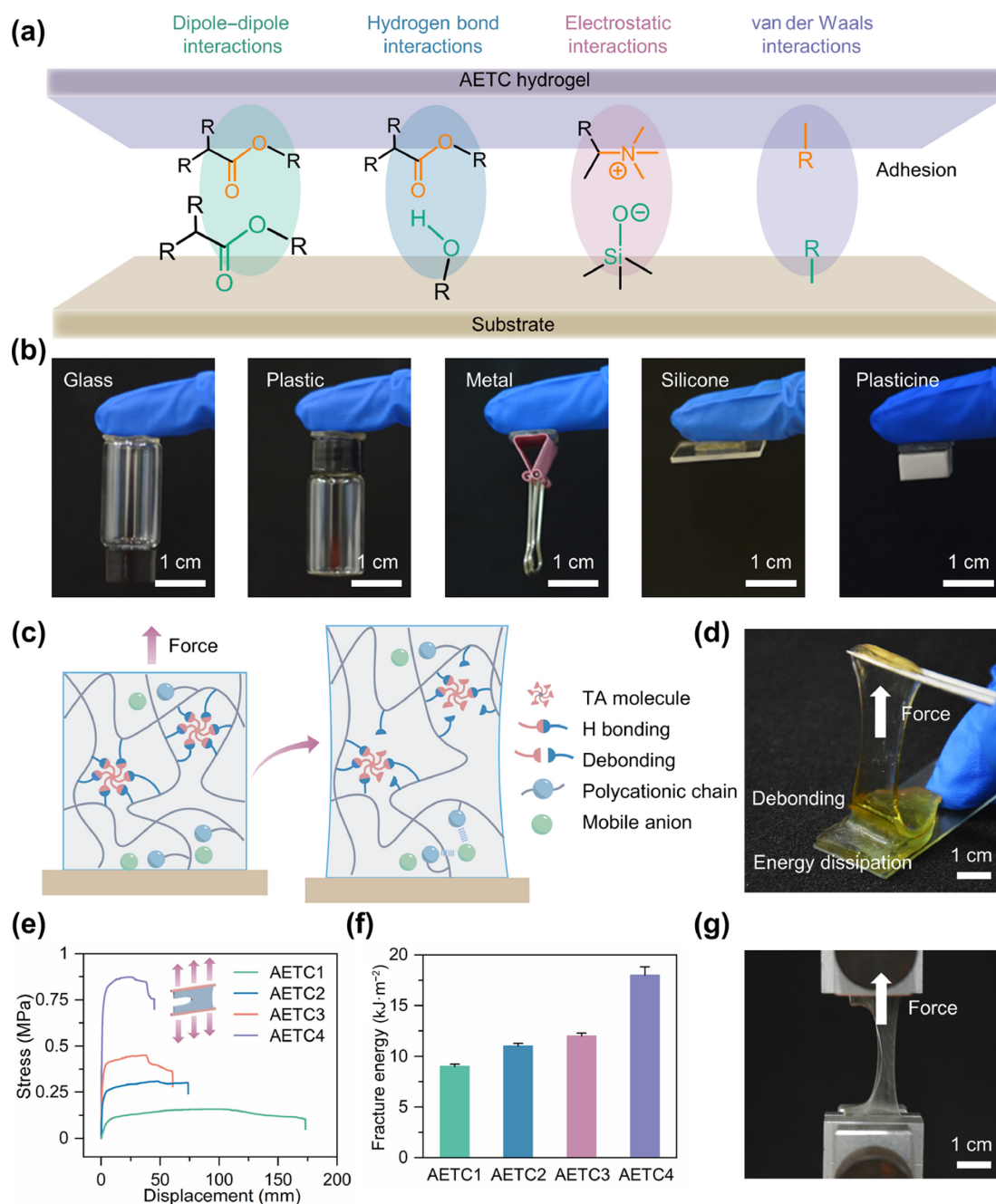


Figure 3 Adhesive properties and mechanisms of the AETC hydrogel. (a) Interfacial adhesion mechanism of the AETC hydrogel on diverse substrates, involving dipole-dipole interactions, hydrogen bonding, electrostatic interactions, and van der Waals forces. (b) Adhesion performance on glass, plastic, metal, silicone, and plasticine substrates. (c) Schematic illustration of intrinsic energy dissipation in the AETC hydrogel. (d) Photograph of the AETC hydrogel during peeling tests. (e) and (f) Force-displacement curves and fracture energy of AETC1 to AETC4 from tearing tests. (g) Photograph showing a notched AETC hydrogel during tearing.

resistance as a function of time after mechanical damage. During needle puncture, a sharp increase in resistance is observed, followed by a rapid return toward the baseline within 3 s (Fig. 4(e)). A comparable resistance recovery is observed after cutting, indicating rapid restoration of electrical continuity upon contact-assisted healing (Fig. 4(f)). The normalized resistance recovery ratios of the puncture-healed and cut-healed hydrogels are both close to 100%, indicating nearly complete recovery of electrical resistance after puncture and cutting damage (Fig. S13 in the ESM). Furthermore, the cut-healed hydrogel maintains a stable resistance of approximately 5.4 k Ω over 100 min, demonstrating long-term

stability of the restored conductive pathway (Fig. S14 in the ESM). The Nyquist plots of the original and cut-healed hydrogels show similar impedance profiles, further confirming effective electrical recovery after contact-assisted healing from cutting damage (Fig. S15 in the ESM). The cut interface gradually becomes indistinguishable over time, indicating progressive restoration of structural continuity (Fig. 4(g)). This contact-assisted healing behavior after complete fracture is further demonstrated by assembling the hydrogel into a Rubik's-cube architecture, where small AETC hydrogel cubes bond together into a larger cube upon contact (Fig. 4(h)). Together with the mechanical recovery, post-

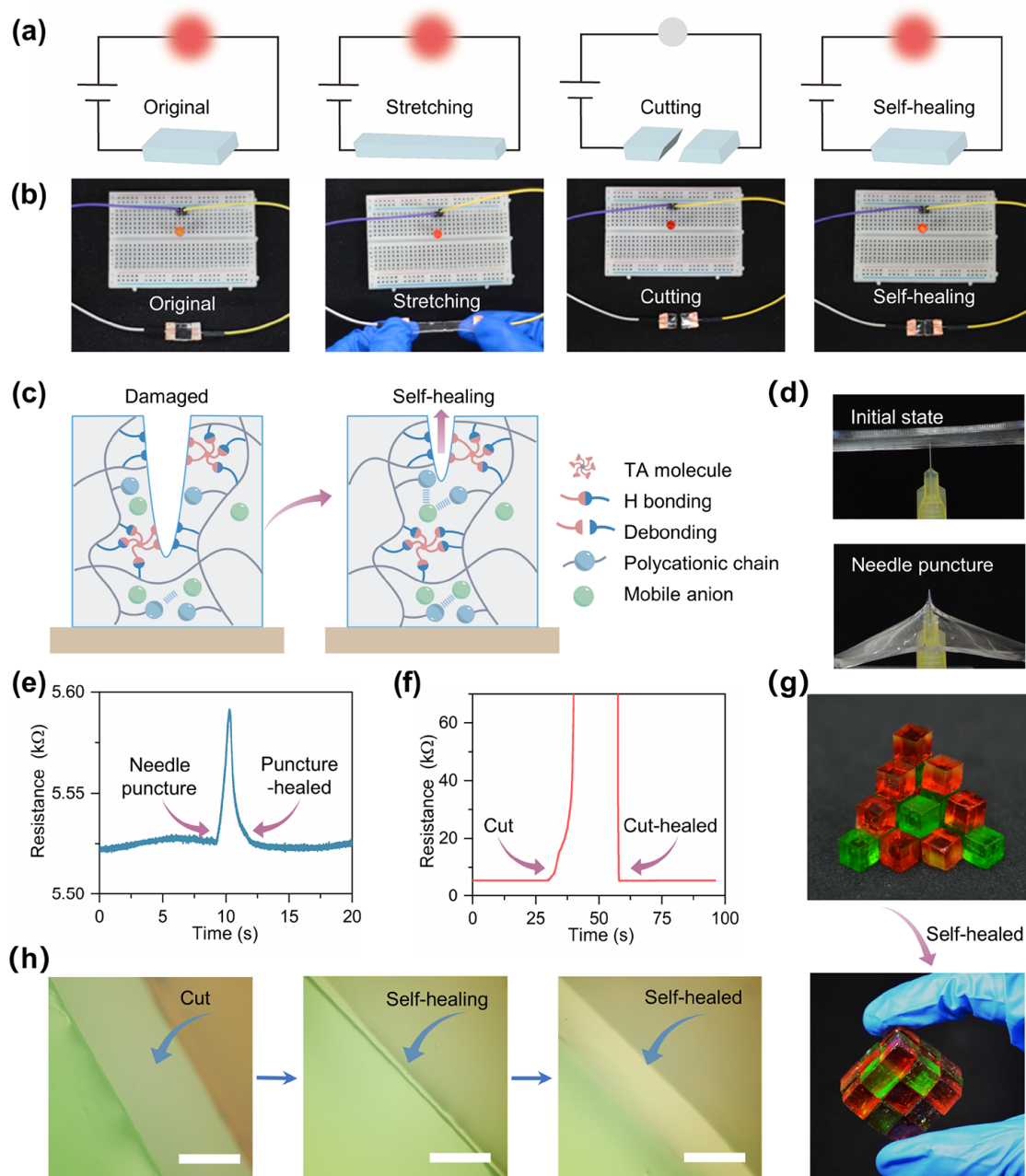


Figure 4 Self-healing properties and mechanisms of the AETC hydrogel. (a) Schematic diagram of LED brightness in original, stretching, cutting, and healed states. (b) LED brightness of AETC hydrogel under original, stretching, cutting, and healed states. (c) Schematic illustration depicting the concept of self-healing through dynamic hydrogen bonds and ionic electrostatic interactions. (d) Puncture resistance tests of AETC hydrogel. (e) and (f) Resistance recovery of AETC hydrogel after needle puncture and contact-assisted healing from cutting damage. (g) Optical images of the contact-assisted healing process of the cut AETC hydrogel. (h) Assembly of small AETC hydrogel cubes into a larger Rubik's-cube structure through contact-assisted healing.

healing mechanical durability, normalized resistance recovery, resistance stability, and impedance comparison shown in Figs. S9–S15 in the ESM, these results demonstrate that the dynamic ionic interactions and hydrogen-bonding network enable effective restoration of both structural integrity and electrical functionality after damage. Hereafter, the optimized AETC4 is denoted as AETC for brevity unless otherwise specified.

2.5 Sensing mechanism and sensing performance of the AETC-based sensor

The AETC hydrogel is a promising candidate material for

electronic devices due to its outstanding mechanical properties, excellent ionic conductivity, and effective self-healing under ambient conditions. An ionotronic sensor is fabricated by positioning a microstructured AETC hydrogel film between two copper electrodes, as shown schematically in Fig. 5(a), with the fabrication process and optical images provided in Fig. S16 in the ESM. A 500- μm -thick polydimethylsiloxane (PDMS) ring is inserted between the top electrode and the hydrogel layer to serve as a spacer, and the entire device is encapsulated with two 50- μm -thick polyimide (PI) films. The interfacial capacitive sensing mechanism is shown in Figs. 5(b) and 5(c). Upon external

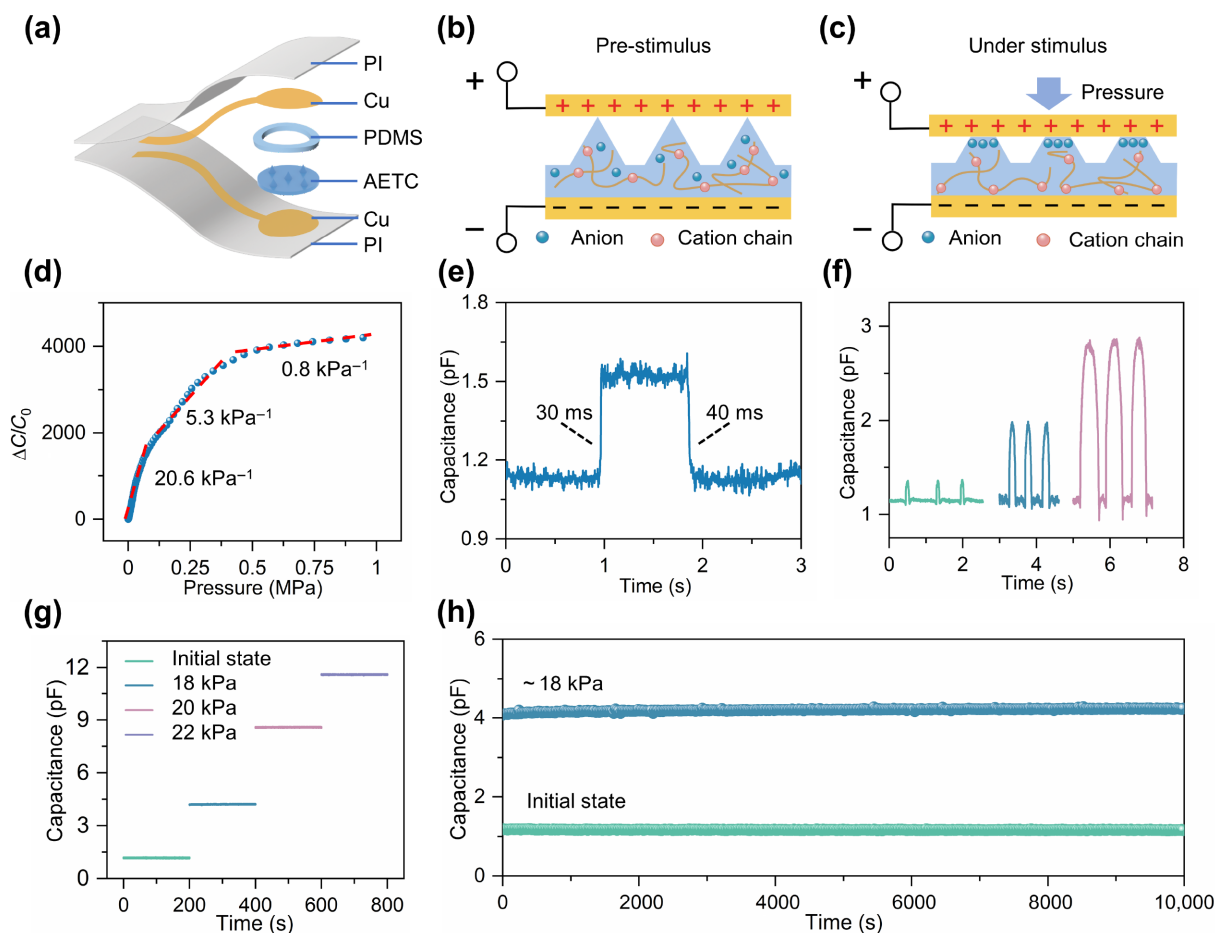


Figure 5 Sensing mechanism and sensing performance of the AETC-based sensor. (a) Schematic of the AETC-based sensor. (b) Schematic of the microstructured AETC hydrogel and electrodes at a pre-stimulus state, where the two are separated and ions are approximately uniformly distributed in the hydrogel. (c) Under mechanical stimulus, the microstructured AETC hydrogel is brought into contact with the electrode, and surface charges on the electrode modulate interfacial ion distribution, leading to the formation of the EDL at the interface. (d) $\Delta C/C_0$ variation of the AETC-based sensor with pressure. (e) Response/recovery time of the AETC-based sensor. (f) Capacitance response of the sensor under stepwise pressure loading. (g) Capacitance variation at the initial state (0 kPa) and under different static pressures (e.g., ~18, ~20, and ~22 kPa). (h) Long-term stability of the sensor at the initial state (0 kPa) and under ~18 kPa static compression over 10,000 s.

mechanical stimulus, the microstructured AETC hydrogel comes into contact with the electronic conductor (electrode), while the interfacial contact state evolves and mobile ions are modulated near the interface in response to the surface charge on the electrode. The resulting capacitive response should therefore be understood as a coupled interfacial effect involving both contact-state evolution and ionic modulation at the hydrogel-electrode interface [41–43].

The sensor demonstrates a sensitivity of 20.6 kPa^{-1} below 100 kPa, which decreases to 5.3 kPa^{-1} over 100–500 kPa and further to 0.8 kPa^{-1} over 500–1000 kPa (Fig. 5(d)). In comparison with most conventional capacitive pressure sensors, the sensor exhibits both higher sensitivity and a broader effective operating range [44–46]. The AETC-based sensor achieves a rapid response time of ~30 ms and a recovery time of ~40 ms (Fig. 5(e)). The achieved response performance is suitable for numerous medical and industrial scenarios, including arterial pulse-wave monitoring and real-time human-machine interface applications [47]. Figure 5(f) shows the real-time capacitance responses of the AETC-based sensor under three levels of finger stimulation of light touch, moderate press, and firm press. The signal exhibits clear, repeatable peaks with a stable baseline, and the peak capacitance increases progressively as the stimulation becomes stronger, indicating clear distinguishability among different touch intensities. Furthermore,

the capacitance exhibits negligible drift at the initial state (0 kPa) and under static compressive pressures of ~18, ~20, and ~22 kPa, confirming its suitability for precise quantitative measurements (Fig. 5(g)). Notably, the capacitance remains stable at the initial state (0 kPa) and under a static load of ~18 kPa over 10,000 s (Fig. 5(h)), confirming the excellent long-term stability and reliability during continuous operation.

2.6 Applications of the AETC-based smart tactile glove

Compared with representative hydrogels reported in recent years, the AETC hydrogel exhibits a balanced combination of high stretchability, mechanical robustness, ionic conductivity, transparency, self-healing capability, adhesion, environmental stability, and sensing performance (Table S1 in the ESM). For wearable ionotronic devices, strong intrinsic adhesion is of particular importance because it facilitates conformal integration with substrates and electrodes, reduces interfacial slippage during deformation, and contributes to stable signal transduction during repeated use. In addition, the self-healing capability is relevant for maintaining device functionality by helping restore ionic pathways and structural continuity after local damage. To demonstrate the practical applicability of the present hydrogel system, a smart tactile

glove is fabricated by integrating the AETC-based sensors onto a textile glove (Fig. S17 in the ESM). During individual finger loading, the five finger-mounted sensors record real-time multichannel capacitance changes, and real-time spatial capacitance heatmaps show the corresponding finger-dependent contact distribution (Fig. S18 and Movie S1 in the ESM). These results confirm that the glove-integrated sensors can independently distinguish tactile inputs from different fingers.

Building on the single-finger response verification, cube grasping is further used as a representative multi-finger tactile task. During cube grasping, the five glove-integrated sensors record stable multichannel capacitance responses from the thumb, index, middle, ring, and pinky channels (Fig. 6(a)). The collected capacitance signals are processed through response normalization and spatial conversion, followed by real-time pressure mapping and shape prediction (Fig. 6(b)). A photograph of the smart tactile glove grasping the cube is shown in Fig. 6(c), and the corresponding real-time capacitance heatmap reveals the spatial contact distribution during cube grasping (Fig. 6(d)). Five objects with different shapes, including cube, cylinder, sphere, cone, and pyramid, are then used for machine-learning-assisted object-shape recognition. The confusion matrix shows high classification accuracy among the five object categories, with an overall recognition accuracy of 99.3% (Fig. 6(e)). This high accuracy is attributed to the shape-dependent contact patterns generated during grasping, which produce distinguishable multichannel capacitance features across different fingers. These results demonstrate the feasibility of data-driven tactile recognition based on the AETC-based smart glove.

In addition, Fig. 6(f) illustrates the smart-glove-based game control system, in which two AETC-based sensors are used as left and right command inputs. The corresponding experimental setup of the direction-recognition test platform is shown in Fig. S19 and Movie S2 in the ESM. Independent AETC-based sensors are integrated into the index finger (sensor 1) and middle finger (sensor 2), which are mapped to left and right commands, respectively, enabling binary directional input. Capacitance signals generated by finger-pressing actions are acquired and processed in real time on a host computer, and the decoded directional outputs are synchronously displayed on the screen to provide immediate visual feedback. Building on this, to further evaluate the usability and robustness of directional-intent decoding in interactive control, the same finger-pressing actions are used as control commands in a two-state obstacle avoidance game. In the game, users are expected to avoid incoming obstacles by issuing binary directional commands. Specifically, users switch the aircraft between two discrete lateral positions (left = -1, right = 1) by pressing sensor 1 or sensor 2, respectively. Obstacles with randomized shapes and trajectories descend from the top of the screen, and the game terminates upon collision. Meanwhile, the host computer records the aircraft position as a function of time, enabling analysis of interaction behavior under controlled visual stimuli.

To demonstrate the effectiveness of directional-intent decoding during interactive gameplay, representative game screenshots are shown in Fig. 6(g), and the direction-recognition interface for left- and right-channel control is shown in Fig. 6(h). The decoded direction outputs (left/right) are displayed over time in Fig. 6(i), together with the corresponding capacitance traces from sensor 1 (left command) and sensor 2 (right command). When the aircraft switches to the left position (-1), sensor 1 exhibits a pronounced capacitance response, whereas sensor 2 remains unchanged;

conversely, transitions to the right position (+1) induce a clear response in sensor 2 while sensor 1 shows no signal output. The temporal evolution of the capacitance signals closely matches the recorded directional states, confirming reliable and unambiguous decoding of finger-press inputs into discrete game commands.

3 Conclusion

In summary, we develop a sea cucumber-inspired ionotronic hydrogel that integrates self-healing under ambient conditions with interfacial capacitive sensing. Reversible ionic and hydrogen-bonding interactions enable self-healing, whereas pressure-induced contact-state evolution coupled with interfacial ionic modulation contributes to capacitive signal transduction. The engineered hydrogel displays outstanding stretchability exceeding 1000%, high ionic conductivity ($> 0.49 \text{ S}\cdot\text{m}^{-1}$), as well as excellent adhesion and effective self-healing capability. We demonstrate that the ionotronic sensor achieves high sensitivity ($\sim 20.6 \text{ kPa}^{-1}$), a wide detection range up to approximately 1 MPa, rapid response/recovery time ($\sim 30 \text{ ms}/\sim 40 \text{ ms}$), and excellent stability under various mechanical loading conditions. As a proof of concept, the hydrogel-based sensor integrated into a smart glove achieves real-time, robust tactile sensing, shape recognition, and directional-intent decoding, enabling smart-glove object discrimination and reliable human-machine interaction control. This work provides a promising route for the design of next-generation smart monitoring electronics for human-machine interaction and wearable sensing platforms.

4 Experimental section

4.1 Materials

[AETC]Cl (80 wt.% in water) was obtained from Aladdin Co., Ltd. (Shanghai, China). TA was purchased from Macklin Biochemical Co., Ltd. (Shanghai, China). 2-Hydroxy-2-methylpropiophenone (Irgacure 1173) was obtained from Bide Pharmatech Co., Ltd. (Shanghai, China). Commercial resin (SP-RH1008) was obtained from Zhejiang Xunshi Technology Co., Ltd. (Hangzhou, China). Silicone rubber elastomer (PDMS, Sylgard 184) was obtained from Dow Corning Co., Ltd. Unless otherwise noted, all chemicals were used without further purification.

4.2 Synthesis and preparation

4.2.1 Synthesis of AETC hydrogels

The AETC hydrogel precursor was prepared by dissolving TA in [AETC]Cl (80 wt.% in water), followed by adding 2-hydroxy-2-methylpropiophenone (Irgacure 1173, 0.5 wt.%) as a photoinitiator. After sonication for 8 h and vacuum degassing, the precursor solution was cured under UV irradiation for 30 min to obtain the AETC hydrogel.

4.2.2 Synthesis of PDMS elastomer

The silicone elastomer base was mixed with the curing agent at a weight ratio of 10:1 and stirred for 30 min. The mixture was cast into a three-dimensional (3D)-printed mold, degassed under vacuum, and cured at 60°C for 8 h to obtain a PDMS elastomer.

4.2.3 Fabrication of AETC-based sensor

An array of microcones (2 mm in diameter and 0.5 mm in height)

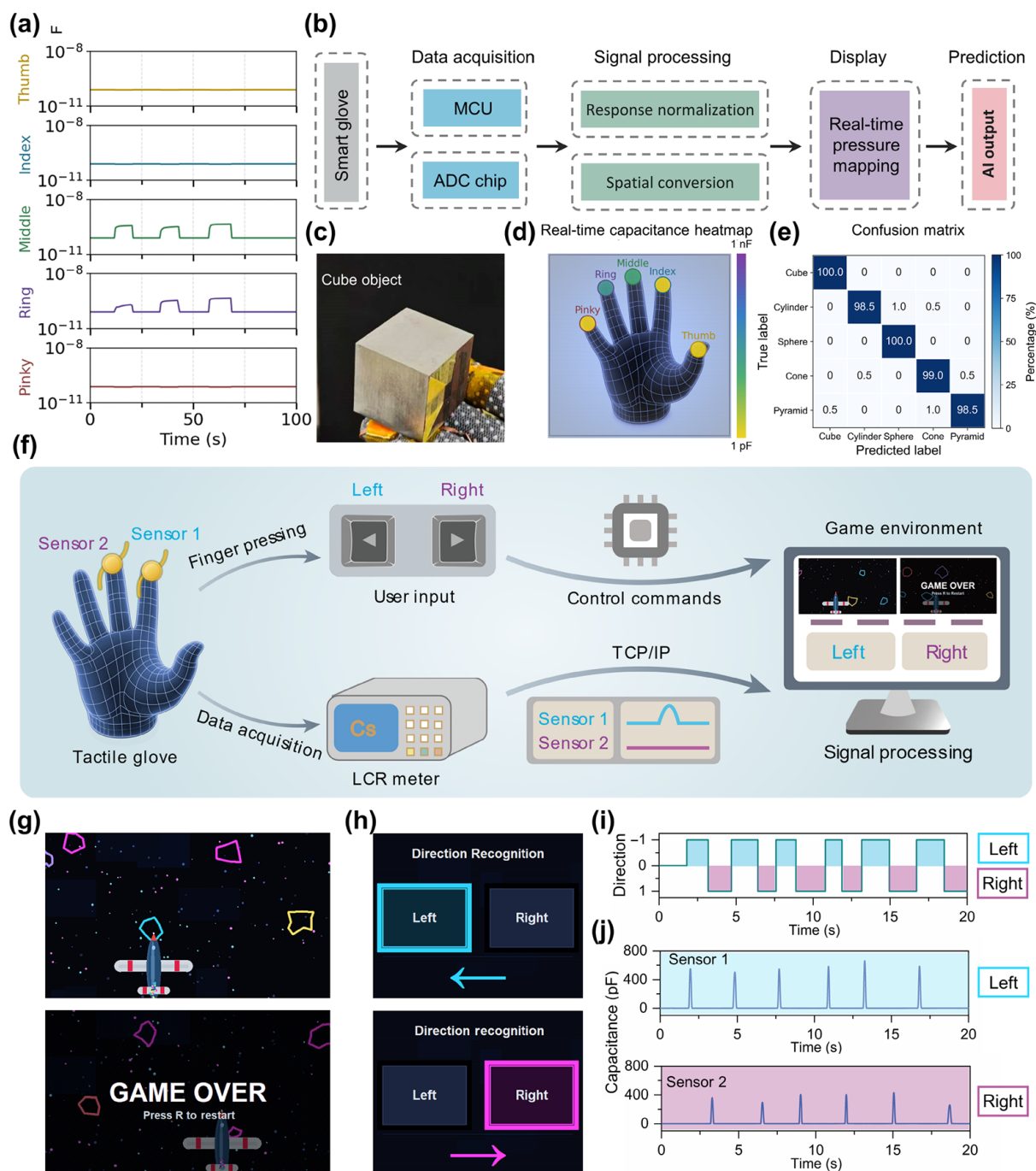


Figure 6 Applications of the AETC-based smart tactile glove. (a) Five-channel capacitance responses during cube grasping. (b) Workflow of tactile data acquisition, signal processing, real-time pressure mapping, and shape prediction. (c) Photograph of the smart tactile glove grasping a cube. (d) Corresponding real-time capacitance heatmap during cube grasping. (e) Confusion matrix for five-class object-shape recognition, including cube, cylinder, sphere, cone, and pyramid, with an overall recognition accuracy of 99.3%. (f) Schematic illustration of a wearable game control system that uses two AETC-based sensors as left and right command inputs. (g) Representative screenshots of the obstacle avoidance game. (h) Direction-recognition interface for left- and right-channel control. (i) Decoded direction outputs and (j) corresponding real-time capacitance responses from sensor 1 and sensor 2.

was fabricated in AETC films by UV curing at room temperature. The cured microstructured AETC films were then assembled with Cu/PI electrodes and a PDMS spacer to construct the sensor.

4.2.4 Fabrication of AETC-based smart glove

The AETC-based smart glove was fabricated by integrating AETC-based sensor units onto all five fingertips, with the AETC microcone surface facing the contact side and fixed with adhesive

tape. The five channels (thumb, index, middle, ring, and pinky fingers) were connected to a multichannel capacitance measurement system.

4.3 Materials characterization

^1H NMR spectra were recorded using an AVANCE NEO 600 spectrometer (Bruker, USA). FTIR spectra were recorded on an INVENIO spectrometer (Bruker, USA) over the range of 400–

4000 cm⁻¹. Field-emission scanning electron microscopy was conducted on an Apreo 2S HiVac FE-SEM (USA). Ultraviolet-visible (UV-Vis) spectra were recorded at room temperature using a UV-3600i Plus spectrophotometer (Shimadzu, Japan) over the wavelength range of 400–800 nm. Optical images were captured using a digital microscope (VHX-500F, Keyence, Japan). Ionic conductivity (σ) was measured using a broadband dielectric impedance spectrometer (Concept 50, Novocontrol, Germany). Mechanical tests were conducted at room temperature using a universal testing machine (HZ-1004, Lixian, China) with a 10 kg load cell.

4.4 Electrical characterizations of AETC-based sensor

All electrical measurements were conducted using an LCR digital bridge meter (TH2840NX, Tonghui Electronics Co., Ltd., China) operated in LCR mode at a frequency of 10 kHz with a 1 V AC signal. The sensitivity (S) was defined as $S = (C/C_0)/P$, where C is the change in capacitance, and C_0 is the initial capacitance, and P is the applied pressure.

4.5 Data acquisition of AETC-based smart glove

For the AETC-based smart glove, capacitance signals were recorded in the scanning mode and streamed to a terminal computer for subsequent processing.

Electronic Supplementary Material: Supplementary material (supplementary experimental details, additional characterization results, mechanical and electrical recovery tests, device fabrication procedures, tactile sensing demonstrations, and comparison with representative hydrogels) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908892>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

K. Z.: Conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing – original draft. L. B. Z. and X. Y. J.: Supervision, project administration. J. W., R. Y. Y., Q. C. D., and H. Y. Y.: Investigation, data curation. All authors: Writing – review & editing.

Use of AI statement

None.

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