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Anti-swelling Zwitterionic Gels with High Stretchability, Conductivity for Wireless Underwater Strain Sensing

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Abstract Gel-based flexible wearable sensors have attracted considerable interest in aquatic environments. However, the development of underwater conductive gel sensors with outstanding anti-swelling, mechanical, and sensing capabilities faces significant challenges. The aim of this study is to develop anti-swelling and conductive zwitterionic gels and investigate their applications in wireless underwater strain sensing. Multifunctional zwitterionic gels were fabricated by copolymerizing [2-(methacryloyloxy) ethyl] dimethyl-(3-sulfopropyl) ammonium hydroxide (SBMA) and acrylic acid (AA) in a mixed solution of aluminum chloride ($AlCl_3$) and poly(vinyl alcohol) (PVA) under ultraviolet light (360 nm). PSBMA was switched from a neutral polymer to a positively charged polymer because of the combination of Al^{3+} with the negative groups SO_3^-. The water molecules were eliminated because of electrostatic repulsion. The gels exhibited anti-swelling properties (swelling ratio <11%), high stretchability (600% strain), and toughness (2451 kJ/m^3). The PPAS-Al^{3+} gel was integrated with a wireless Bluetooth system to construct underwater wearable strain sensors that could accurately capture the signals caused by human joint movements and speech recognition even in water. Antibacterial activity (>98.9% inhibition) and stable wireless sensing have potential applications in the fields of wearable sensors, underwater communication, and intelligent healthcare.

Keywords Anti-swelling; Zwitterionic gels; Wireless wearable sensor; Multifunction

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INTRODUCTION

Conductive gels have gained considerable attention owing to their applications in wearable sensors, soft robots, supercapacitors, and energy storage devices. Wearable underwater sensors are important for monitoring drivers' physiological signals, communicating with each other, or detecting sound waves.[1–3] However, the strong water absorption ability and high swelling decrease the strength, conductivity, and sensing capacity of the gels. Anti-swelling gel sensors have great potential for ocean exploration, marine biological research, and underwater communication.[4–6]

Various strategies have been proposed to design anti-swelling conductive gel sensors by introducing hydrophobic chain segments, carbon materials, conductive polymers, or ionic polymers into the gel matrix.[7–9] Among them, zwitterionic chemical compounds [2-(methacryloyloxy)ethyl] dimethyl-(3-sulfopropyl) ammonium hydroxide (SBMA) is a promising candidate for constructing anti-swelling conductive gels because the corresponding polymer poly(2-(*N*-3-Sulfopropyl-*N*,*N*-dimethyl ammonium) ethyl methacrylate) (PSBMA) contains the cationic group quaternary ammonium (R_3N^+) and anion group sulfonate (SO_3^-), which could endow the gels with good conductivity.[10–12] Moreover, PSBMA could be switched from a neutral to a positively charged state by protonating the negatively charged $-SO_3^-$ group of SBMA. Electrostatic repulsion reduces the osmotic measure and endows the gel with outstanding anti-swelling properties.[10,13,14] Most importantly, the double bonds of SBMA are easy to copolymerize with many olefin monomers, which is beneficial for optimizing gel performance. However, most gel-based sensors are severely limited for underwater sensing applications because of their soft texture, low strength, poor toughness, weak conductivity, and insufficient strain sensitivity.[15,16] Furthermore, the requisite for external wiring poses a fundamental challenge to the miniaturization and portability of sensing systems, which significantly restricts their application in wearable devices or remote monitoring instruments.[17,18]

Based on this, we propose that it is possible to construct zwitterionic gels with satisfactory anti-swelling, high stretchability, and conductivity, as well as wireless underwater strain sensing, using a simple, efficient, and green strategy. In this study, poly(vinyl alcohol) (PVA) and poly(acrylic acid) (PAA) were chosen for the composite with PSBMA, and Al^{3+} was introduced into the gel matrix to enhance the conductivity and mechanical properties of anti-swelling gel sensors. Because

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PVA and PAA have the advantages of high hydrophilicity, stretchability, and excellent film-forming ability, they are widely used to fabricate functional gels with high toughness, self-healing properties, and sensing capabilities.[19,20]

In this study, simple and green ultraviolet radiation polymerization was used to copolymerize SBMA and acrylic acid (AA) in a mixed solution of aluminum chloride hexahydrate and PVA crosslinked with ethylene dimethacrylate (EDGMA). The prepolymer was frozen at –20 °C for 2 h to accelerate the crystallization of PVA, forming the PVA-P(AA-SBMA)-Al^{3+} (PPAS-Al^{3+}) gels with physical points. The introduction of metal ions into the gel matrix involves the construction of metal coordination because Al^{3+} can combine with SO_3^-.[21–23] However, the positively charged R_3N^+ groups remained, and the electrostatic repulsion among the cations contributed to the anti-swelling effect. Moreover, Al^{3+} could also interact with the carboxyl groups of AA and hydroxyl groups of PVA, which contributed to the high toughness (2451 kJ/m^3) and stretchability (up to 600% strain). The anti-swelling PPAS-Al^{3+} gels were integrated into a wireless Bluetooth system to construct flexible underwater wearable strain sensors. Wireless sensors can accurately capture motion-induced signals, enabling real-time human movement monitoring and effective speech characterization. It could also maintain structural integrity and a stable relative resistance response over 400 cycles at 50% strain or even after immersion in water for 15 days. Anti-swelling and Bluetooth-enabled wireless sensing provide gels with broad potential applications in underwater communication, deep-sea exploration, human-computer interaction, and intelligent healthcare.

EXPERIMENTAL

Materials

Poly(vinyl alcohol) 1799 (PVA, 99% alcoholysis degree), [2-(methacryloyloxy) ethyl] dimethyl-(3-sulfopropyl) ammonium hydroxide (SBMA, ≥ 97%), acrylic acid (AA), ethylene glycol dimethacrylate (EDGMA, 98%), 2-hydroxy-4′-(2-hydroxyethoxy)-2-methylpropiophenone (Irgacure 2959, 98%) were all purchased from Aladdin. Aluminum chloride hexahydrate ($AlCl_3{\cdot}6H_2O$, 97%) was purchased from Macklin.

Preparation of PPAS-Al^{3+} Zwitterionic Gels

The typical PPAS-Al^{3+} gel was fabricated as follows (taking AA:SBMA = 2:1 as an example): 0.7 g of PVA was dissolved in 9 mL of deionized water at 90 °C, obtaining solution A. 4 g of AA, 2 g of SBMA, $AlCl_3$ (0.15 mol/L), 0.06 g of Irgacure 2959, and EGDMA were dissolved in 3 mL of deionized water (solution B), which was added to solution A and stirred for 30 min. The mixed solution was poured into a mold and irradiated under a UV lamp (365 nm, 500 W) for 6 min. After that it was transferred to a refrigerator at –20 °C for 2 h, and the PPAS-Al^{3+} zwitterionic gel was obtained, named as PPA_xS_y-$Al^{3+}{}_n$ (x:y = 1:2, 1:1, 2:1; n = 0.15, 0.25, 0.35 mol/L).

Characterization

Fourier transform infrared spectroscopy (FTIR, TENSOR 27, BRUKER, USA) was used to analyze the chemical structures of the PPA, PPAS, and PPAS-Al^{3+} gels in the range of 500–4000 cm^{-1}. Scanning electron microscopy (SEM, Sigma 300, Zeiss, Germany) was used to analyze the surface morphology of the gels. Energy-dispersive X-ray spectroscopy (EDS; EDX 7000, Shimadzu, China) was used to determine the elemental content. The tensile properties of the gels were tested using an electromechanical universal testing machine (RGM-6005; Shenzhen Reger Co., Ltd.) at a speed of 255 mm/min. The dynamic swelling properties of the PPAS-Al^{3+} gel were determined by the gravimetric method using an electronic balance with an accuracy of 10^{-4} g (Mettler AL204, Switzerland).

Sensing Performance Testing

The conductivity of the gels was measured using a CHI660E electrochemical workstation. The gel was wrapped with conductive copper foil tape and connected to the electrodes of an electrochemical workstation. The ionic conductivity was calculated using Eq. (1):

$$\text{Conductivity} = \frac{L}{RS} \tag{1}$$

where R is the resistance of the sample and L and S are the actual length and cross-sectional area of the gel sample, respectively.

The real-time I-t curve of the gel sample under DC voltage was recorded, and the relative resistance change rate was calculated according to Eq. (2) to evaluate the sensing performance.

$$\frac{\Delta R}{R_0} = \frac{R - R_0}{R_0} \times 100\% \tag{2}$$

where R and R_0 represent the resistance of the deformed and initial strains, respectively. The sensitivity of the gel sensor was determined using the gauge factor (GF), which is the ratio of the relative resistance change to the strain (ε) (Eq. 3):

$$\text{GF} = \frac{\Delta R/R_0}{\varepsilon} \tag{3}$$

For the underwater stain sensing testing, the copper sheet and gel were wrapped with waterproof tape to monitor finger joint movements and Morse code. The gel was directly attached to the skin at different parts of the human body (throat, fingers, wrist, elbow, *etc.*) using pressure-sensitive tape, which was combined with a Bluetooth system to assemble a wireless wearable sensor. It can monitor resistance changes caused by stretching, pressing, and human joint movements.

Antibacterial Performance Testing

The plate counting method was used to evaluate the antibacterial performance of gram-positive *Staphylococcus aureus* (*S. aureus*, ATCC 25923) and gram-negative *Escherichia coli* (ATCC 25922). The samples were placed in a 24-well plate and sterilized under a UV lamp for 30 min. Next, 1 mL of PBS containing *S. aureus* suspension (1×10^8 CFU^{-1}) was added, and PBS without gel samples was chosen as the control group. 50 μL of *S. aureus* suspension were taken from each well and spread on MH agar plates after incubation at 37 °C for 12 h, which were then incubated at 37 °C for 24 h. Digital images were recorded, and the colonies. The antibacterial efficiency was calculated using Eq. (4).

$$\text{Antibacterial ratio (\%)} = \frac{C_{\text{Blank}} - C_{\text{Sample}}}{C_{\text{Blank}}} \times 100\% \tag{4}$$

where C_{Blank} and C_{Sample} are the colony counts for the blank and sample groups, respectively.

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RESULTS AND DISCUSSION

Preparation and Structural Characterization of PPAS-Al^{3+} Gel

Fig. 1 illustrates the gel formation process and gelation mechanism of PPAS-Al^{3+} gel. One can see that the mixed solution of AA, SBMA, PVA, and Al^{3+} transforms into a white opaque gel after being irradiated under UV and frozen at –20 °C for 2 h. PAA, PSBMA, and EDGMA were chemically crosslinked, and the partially crystalline PVA chains arranged orderly, acting as the physical crosslinking points. Moreover, intramolecular and intermolecular hydrogen bonds existed among the PVA, PAA, and PSBMA macromolecular chains. The hydrogen bonds, electrostatic interactions, and metal coordination bonds between Al^{3+} and P(SBMA-*co*-AA) not only promoted gelation, but also endowed the gels with excellent mechanical properties and conductivity.

The copolymerization of AA and SBMA was confirmed by FTIR (Fig. 2). The bands at 3262 cm^{-1} are ascribed to the O—H stretching vibration of carboxyl and hydroxyl groups in the PAA and PVA chains, respectively. Compared to PPA and PPAS, PPAS-Al^{3+} showed a broader absorption band and significantly reduced peak intensity. This is because Al^{3+} chelates with hydroxyl groups, thereby restricting its vibration. The C—H stretching vibration of the PVA, PAA, and SBMA polymer backbones can be observed at 2920 cm^{-1}. The peak at 1713 cm^{-1} arises from the C=O stretching vibrations of PAA and SBMA. The absorption peak at 1430 cm^{-1} is assigned to the C—H bending vibration of PVA and AA, as well as the asymmetric bending vibration of $-N(CH_3)_2-CH_3$ in PSBMA macromolecular chains.[24] The C—O stretching vibrations of PSBMA and PVA appeared at 1160, 1090 cm^{-1} respectively. Compared with PAA and PAAS, PAAS-Al^{3+} exhibits an absorption peak at 1038 cm^{-1}, which corresponds to the S=O stretching vibration of the sulfonate group. The formation of new peaks indicated the polymerization of SBMA in the gel matrix.[25]

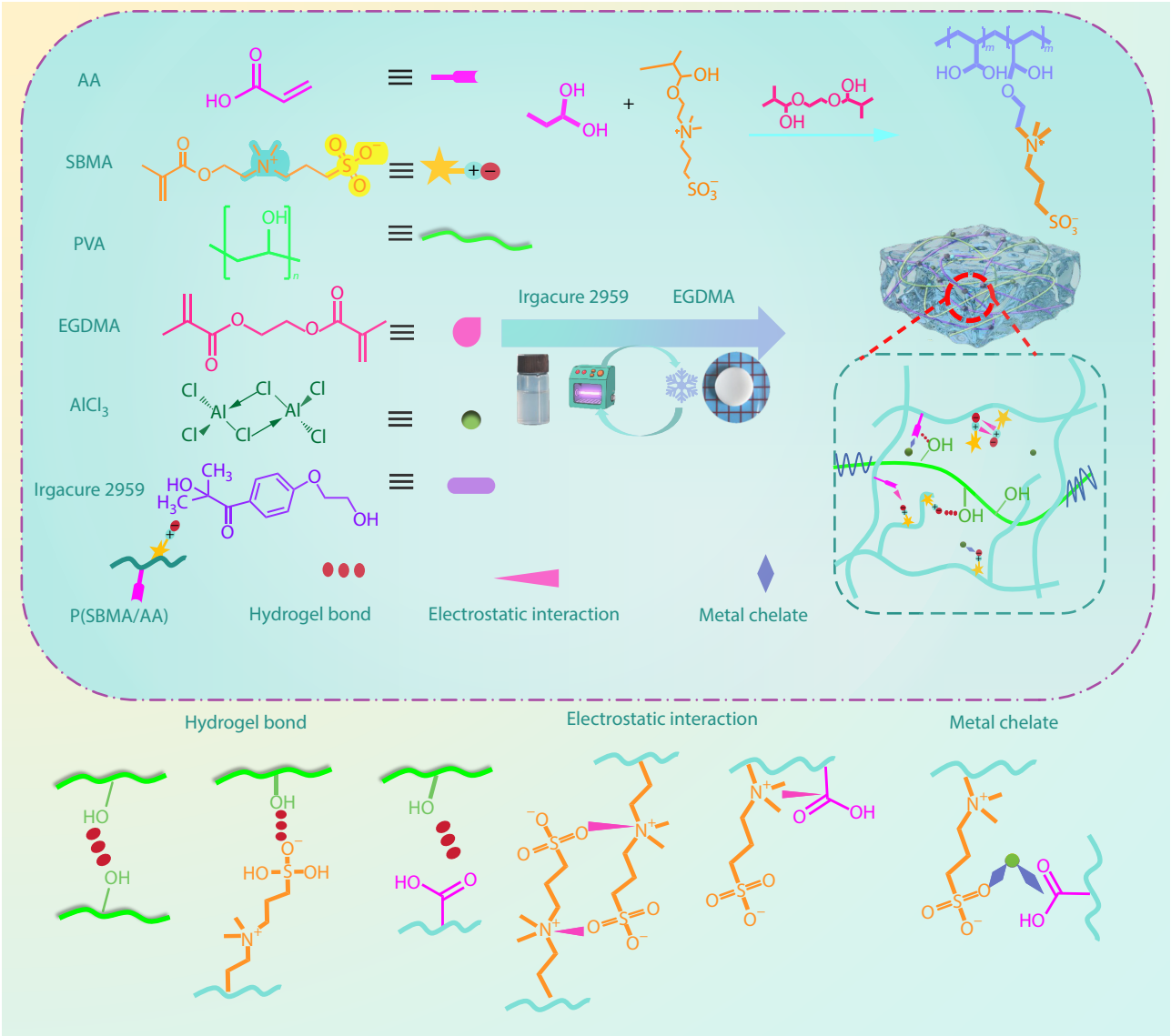

Fig. 1 Preparation process, formation mechanism diagram of the PPAS-Al^{3+} gels.

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Tensile Properties and Microscopic Morphology of PPAS-Al^{3+} Gels

High stretchability and robust mechanical toughness are essential for gel strain sensors to ensure a reliable sensing performance. Figs. 3(a) and 3(b) show the PPAS-Al^{3+} gel exhibits excellent mechanical properties, which could maintain the structural integrity under various deformations, including stretching, twisting, knotting, or loading a weight of 500 g. The mechanical properties of the gels depend on the monomer ratio of AA to SBMA and Al^{3+} content. The increasing PAA enhanced the tensile strength and elongation at break owing to the increasing density of carboxyl groups, which facilitated the formation of metal chelation with Al^{3+} concentration.[26] Figs. 3(c)–3(f) show the PPA$_2$S$_1$-Al$^{3+}_{0.35}$ gel possesses maximum elongation at break (600%) and tensile strength (700 kPa). Young's modulus and toughness were 200 kPa and 2451 kJ/m^3, respectively. The enhanced tensile property is attributed to the increased metal chelation and electrostatic interactions between Al^{3+} and the sulfonate and carboxyl groups, forming more physical crosslinking points among different polymer chains.[24] The high flexibility of gels makes them suitable for assembling strain sensors. The SEM images revealed that PPAS displayed a loose and porous morphology, whereas PPAS-Al^{3+} exhibited a denser surface morphology with a uniform wrinkled structure (Fig. 3g). This indicates good compatibility among the three macromolecular chains within the gel matrix.

Anti-swelling Properties of PPAS-Al^{3+} Gels

The anti-swelling ability is a critical factor for gels to achieve sta-

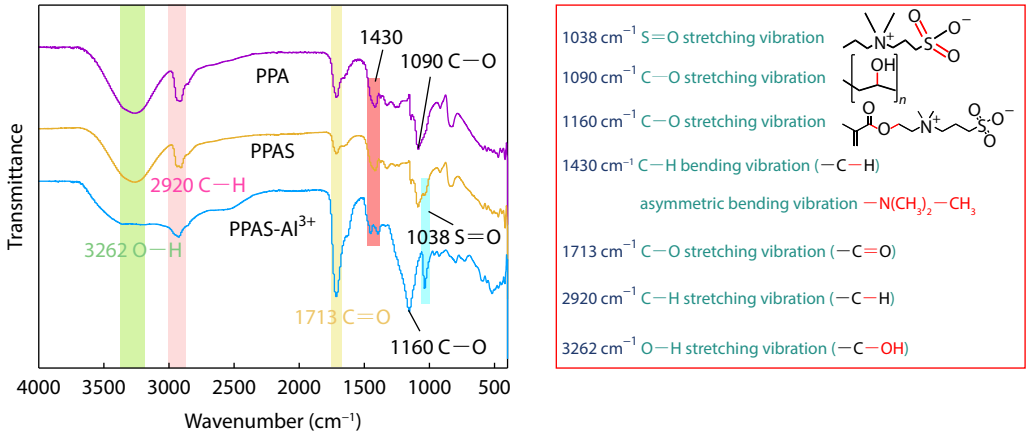

Fig. 2 Infrared spectra of PPAS-Al^{3+} gels with different compositions.

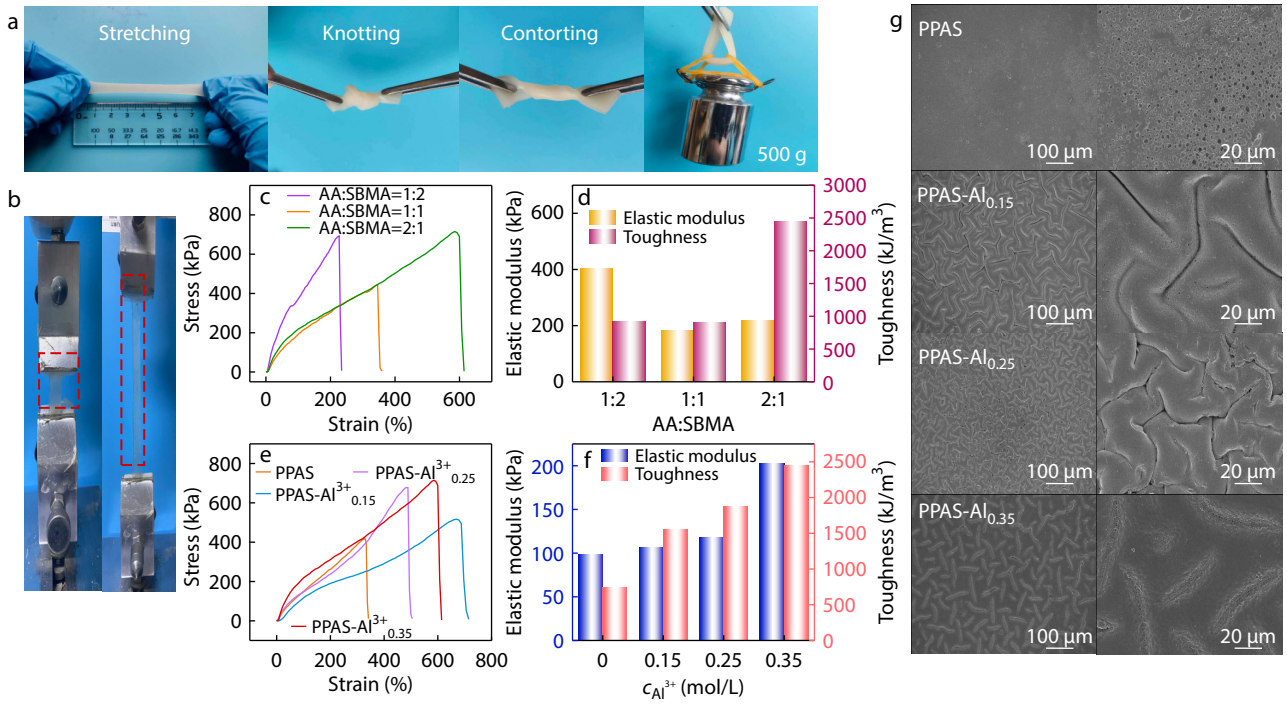

Fig. 3 (a) Macroscopic images of a PPAS-Al^{3+} gel being stretched, twisted, knotted, and lifting a 500 g weight; (b) Macroscopic view under tensile deformation; (c) Stress-strain curves and (d) elastic modulus and toughness of gels with different AA:SBMA ratios; (e) Stress-strain curves and (f) elastic modulus and toughness of gels with varying Al^{3+} contents; (g) SEM images of different PPAS-Al^{3+} gels.

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ble underwater sensing when employed as sensory devices.[27] Figs. 4(a) and 4(b) show the volume had no significant change even after immersing the gel in water for 15 days, and excellent tensile properties were still maintained underwater. The equilibrium swelling ratios of PPAS-Al^{3+} gels with different compositions are shown in Fig. 4(c). It was found that the PPAS gel exhibited a swelling ratio of 11%, which decreased with increasing Al^{3+} content. The anti-swelling performance is derived from the association between cationic Al^{3+} and the sulfonate groups $-SO_3^-$, the PSBMA was switched from neutral to positively charged, creating charge repulsion that prevents water penetration.[28,29] The gel was in slight contact with ethanol and acidic solutions, and its swelling ratio in an alkaline medium was effectively suppressed below 20% (Fig. 4d). This is attributed to the unique antipolyelectrolyte effect of the ampholytic ions under alkaline conditions, which promotes chain dissociation and effectively counteracts osmotic swelling through charge screening mechanisms.[30,31] Figs. 4(e)–4(h) show that compared with the PPAS gel, the tensile strength, elastic modulus, and toughness of PPAS-Al^{3+} gels slightly increased in water and seawater. The elongation at break was maintained at approximately 300%, and the tensile strength reached 500 and 555 kPa, respectively, even when the gels were immersed in an aquatic environment for 3 days.

Conductivity of PPAS-Al^{3+} Gels

The cation and anion groups in the PSBMA macromolecular chains and Al^{3+} of $AlCl_3$ could be transported swiftly within the transport channels of the gel matrix under an electric field. The free-moving ionic groups endow the gel with excellent conductivity, which is important for the application of gel sensors. Figs. 5(a)–5(c) show the PPAS-Al^{3+} connected in the circuit illuminated a Light Emitting Diode (LED) bulb underwater, and the brightness decreased when the gel was stretched. This is because the polymer chains were elongated and the ionic transport channels became narrow, leading to an increase in the relative resistance ($\Delta R/R_0$).[32–34] The LED was re-lighted when the cut gel fragments were retouched, and the electrical signals recovered rapidly within 0.3 s. Compared with PPAS gel (0.14 S/m), the PPAS-$Al^{3+}_{0.35}$ gel exhibited enhanced conductivity, reaching a maximum of 1.31 S/m (Fig. 5d). Al^{3+} serves as a physical crosslinker to enhance the electrical conductivity and mechanical properties.[35] The gel retained good conductivity (0.6 S/m) even after immersion in water for 72 h (Fig. 5e).

Strain Sensing Properties of PPAS-Al^{3+} Gels

The gel strain sensors were assembled by connecting the gels with copper sheets and integrating them into a closed circuit. The high stretchability and conductivity render the PPAS-Al^{3+}

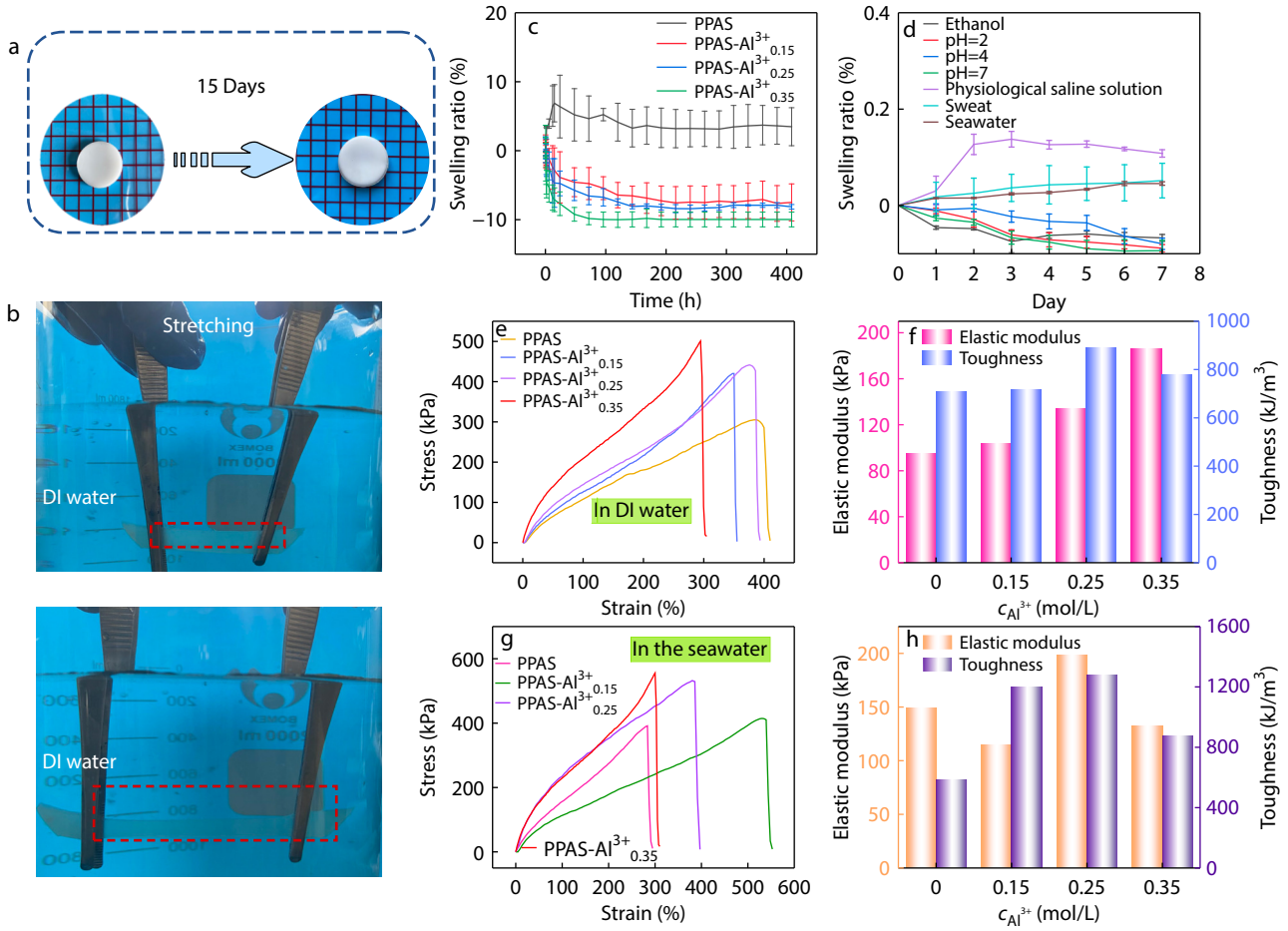

Fig. 4 (a) Macroscopic images of the gel after 15-day immersion in deionized water and (b) underwater stretching; (c) Swelling ratio of PPAS gel with different Al^{3+} contents; (d) Swelling curves of PPAS-Al^{3+} gel in different solutions; (e) Stress-strain curves and (f) elastic modulus and toughness diagrams of the gel after 3-day immersion in deionized water; (g) Stress-strain curves and (h) elastic modulus and toughness diagrams of the gel after 3-day immersion in seawater.

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gel highly suitable for strain sensing. Figs. 6(a) and 6(b) show the relative resistance increased linearly when the gel sensors were stretched from 0% to 400%, with a gauge factor (GF) of 2.02 (200%–400%). The strain-responsive behavior of the gels was attributed to their soft, elastic, and conductive structures. The gel matrix was stretched under extra force, reducing the spacing between the polymer chains. The ion transport channels were narrowed, increasing the resistance to ion migration. Thus, the output electrical signal was changed to realize the stain sensing. Furthermore, the gel could be stretched 100 times repeatedly at a strain of 50%, and no signal degradation was observed (Fig. 6c), indicating the excellent durability and stability of the gel strain sensor.[36] After 3 days of water immersion, the GF of the gel sensors still responded to a wide range of strains from 0% to 400%, maintaining a maximum value of 1.92, which was similar to the value of the original gel (Figs. 6d). Figs. 6(e) and 6(f) show the gel exhibits temperature and pressure responsiveness; the $\Delta R/R_0$ decreases with temperature and dis-

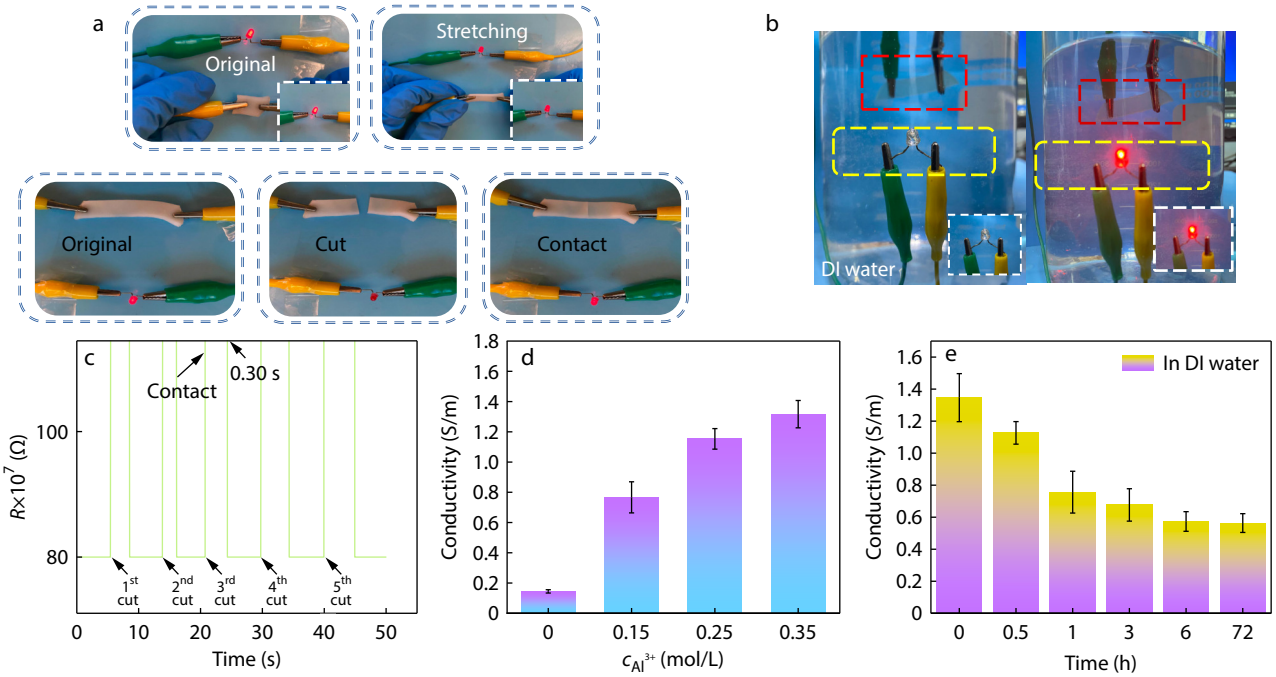
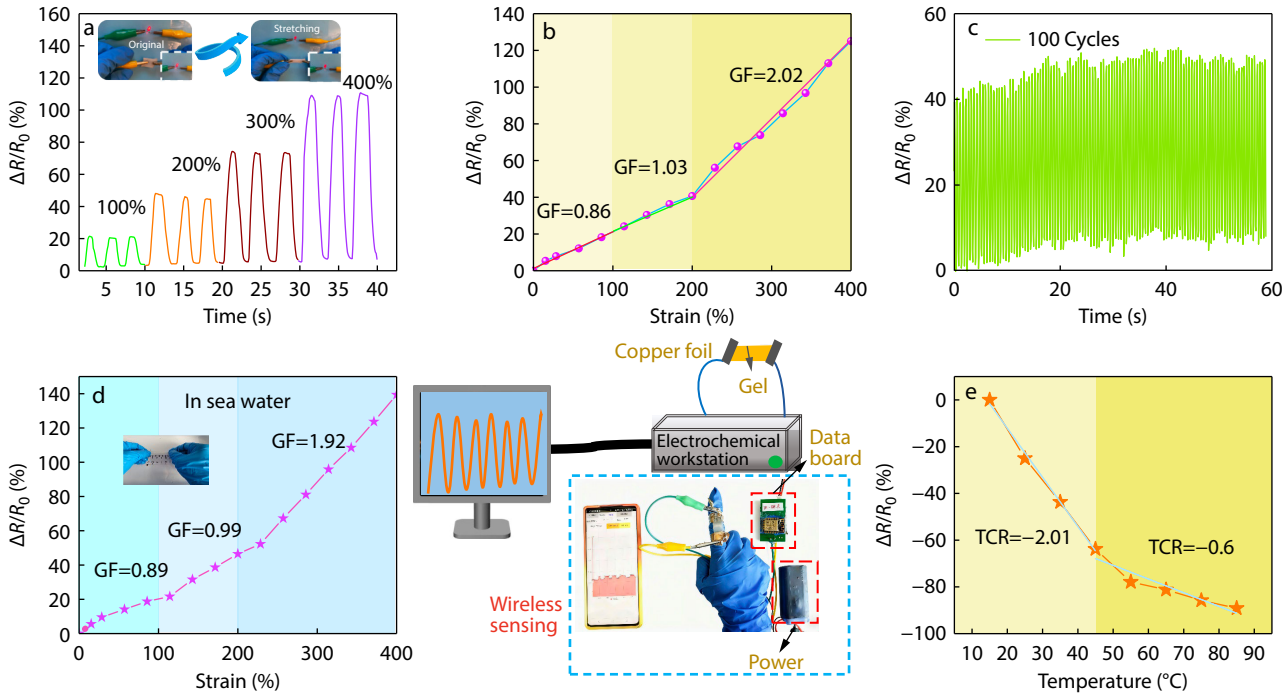


Fig. 5 (a) LED illumination behavior of the gel during cutting and stretching under air and (b) underwater conditions; (c) Conductivity recovery during cutting-healing cycles; Conductivity of (d) different PPAS-Al^{3+} gels, and (e) during prolonged water immersion.



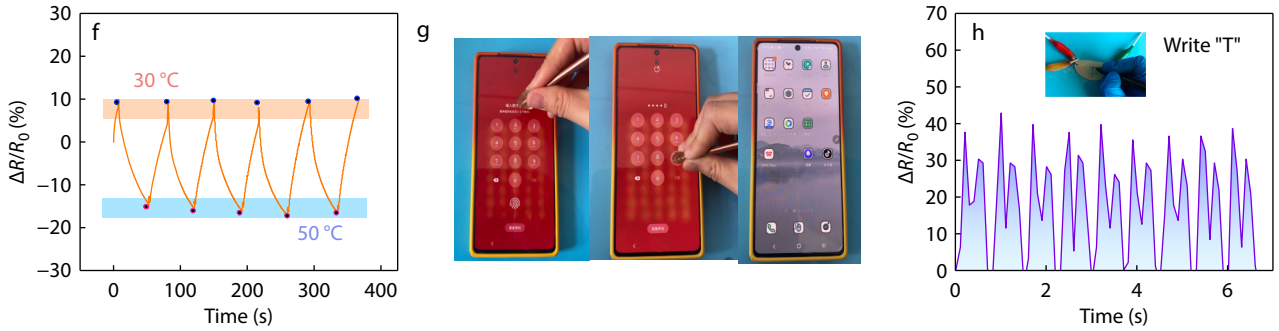


Fig. 6 (a) The relative resistance change curves and (b) GF of the gel based sensors at different strain ranges (100%–400%) and (c) stretching 100 cycles at 50% strain; (d) Underwater sensitivity and (e) temperature coefficient of resistance (TCR) of the PPAS-Al^{3+} gel; (f) Resistance change curve under 10 cycles at 30 and 50 °C; (g) The gel sensors used as an electronic contact pen to simulate the phone unlocking process and (h) relative resistance change of the gel-based writing pad during handwriting of the letter "T".

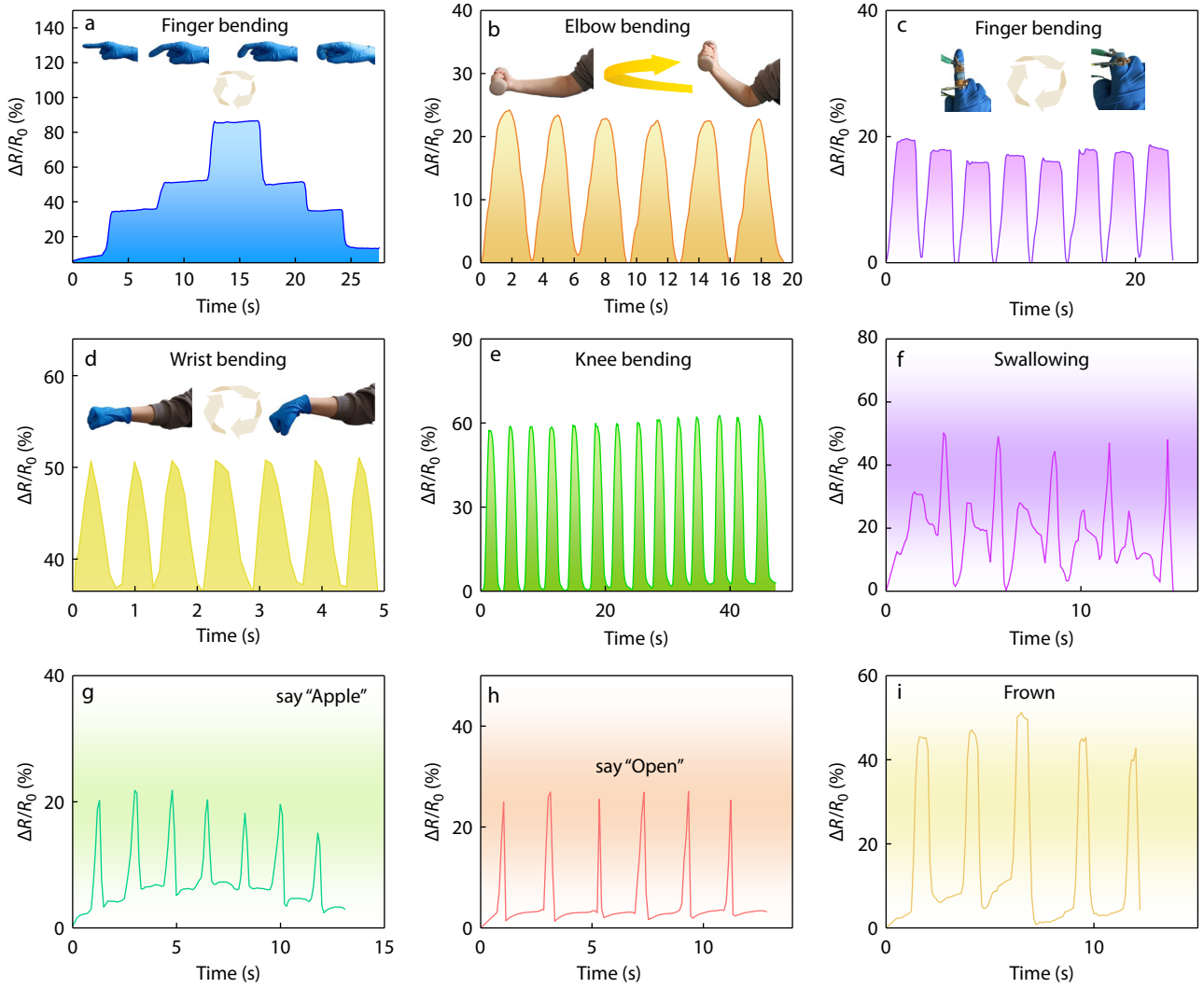


Fig. 7 The applications of the wireless wearable sensor based on PPAS-Al^{3+} gels used for detecting the human join movement, including (a, c) fingers, (b) elbows, (d) wrists, and (e) knees, (f) swallowing, (g) say "Apple", (h) "Open" and (i) frowning.

plays excellent repeatability from 30 °C to 50 °C for 10 cycles, enabling accurate temperature sensing. The PPAS-Al^{3+} gel was covered on the electronic stylus to assemble the pressure-sensitive touchpad, which could unlock the smartphone and recognize intelligent writing (Figs. 6g and 6h). This intelligent response is expected to accelerate the application of future flexible electronic devices.

Wireless Strain Sensing Properties of PPAS-Al^{3+} Gel

Based on the excellent strain-sensing performance of the PPAS-Al^{3+} gel, wireless wearable sensors integrated with a Bluetooth

transmission module were constructed to solve the inconvenience issues caused by the complex circuits. By attaching the flexible sensor to different joints of the human body (including knuckles, wrists, elbows, and knees), the sensors could accurately capture the signal changes arising from limb movement and real-time monitoring of human movement on the mobile device terminals (Figs. 7a–7e). When the volunteer performed subtle movements (swallowing or frowning), the gel sensor monitored the specific muscle movements precisely, converting them into stable and reproducible electrical signals (Fig. 7f). The sensor could distinguish effectively different speech characteristics (such as "Open" and "Apple") when it was attached to the throat. The results showed that the relative resistance change curves corresponding to different pronunciations exhibited different peaks (Figs. 7g–7i), indicating that the gel sensor had a speech pattern recognition capability. Gel sensors have wide applications and great potential in joint function assessment, speech interaction systems, intelligent healthcare, and emotion recognition.

Underwater Sensing Applications of PPAS-Al^{3+} Gel

Underwater strain sensing has attracted increasing attention because of the development of deep-sea exploration and underwater robots. The high conductivity, anti-swelling properties, and strain sensing endow gel sensors with great potential for

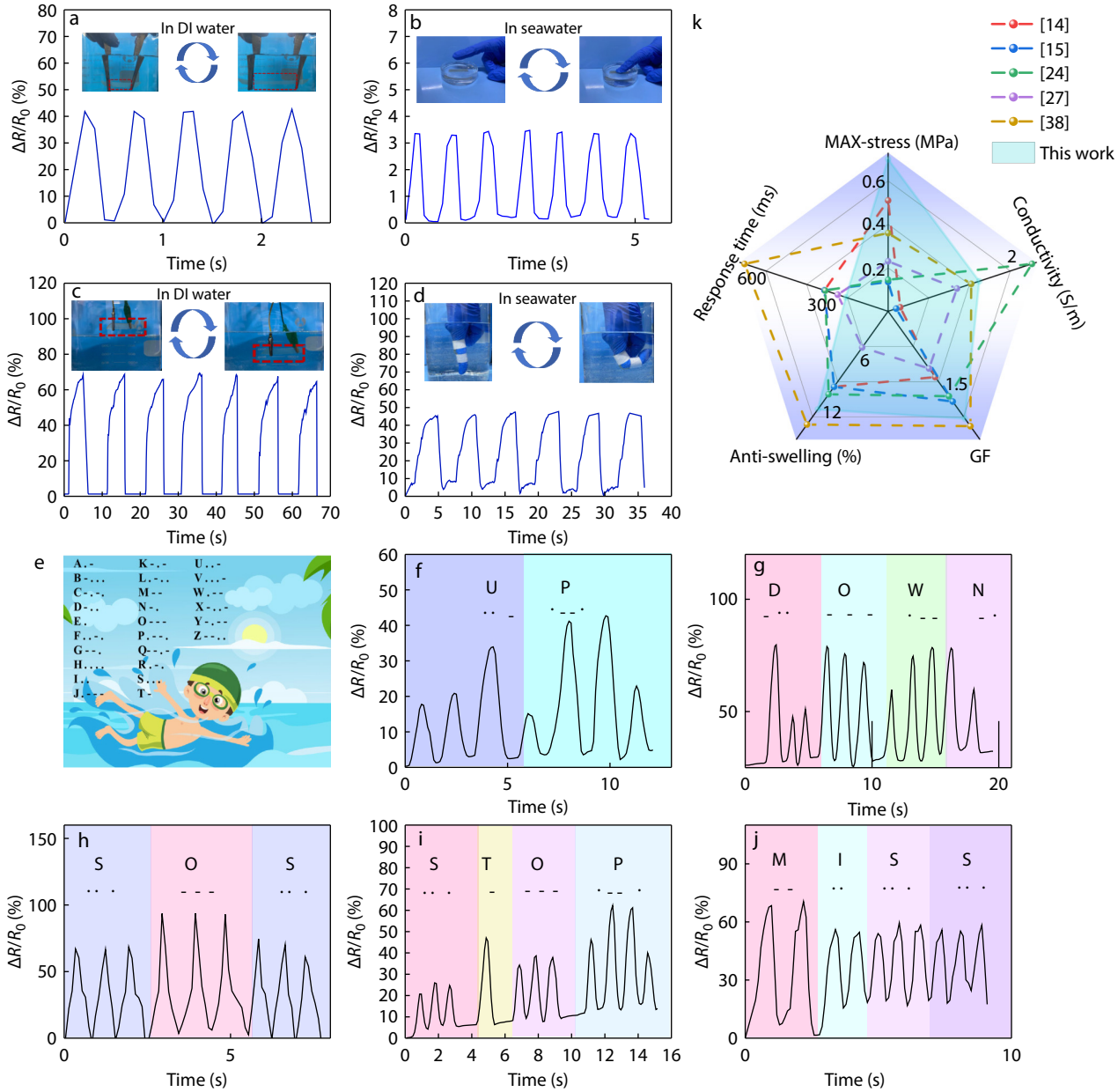


Fig. 8 Resistance changes of the wireless wearable sensor applied for under seawater physiological monitoring (a) during stretching, (b) pressing, (c) up-and-down movements, and (d) finger bending, (e) the detection of the Mose code signals sent by swimmers underwater, (f) "UP", (g) "DOWN", (h) "SOS", (i) "STOP", (j) "MISS", (k) the comparison of the comprehensive performance between the present work and other acrylic-based or zwitterionic-based sensors.

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underwater communication and real-time signal detection. Figs. 8(a)–8(d) show the gel sensors responded in real time under seawater pressing, bending, immersion, and stretching by detecting the relative resistance changes. Moreover, the gel sensors can accurately recognize the signals sent by the Mose code underwater. For the Morse code mechanism, messages consisting of letters or numbers can be represented and transmitted by various sequences of dots and dashes. Thus, it can be effectively utilized for emergency distress signaling by deep-sea divers or in underwater communication scenarios. Figs. 8(f)–8(k) display "UP," "DOWN," "SOS," "STOP" and "MISS" signals sent by the swimmer underwater could be accurately detected. Compared with acrylic-based or zwitterionic-based sensors, the PPAS-Al^{3+} gel sensor exhibited superior performance in the case of stretchability, anti-swelling, thermal responsiveness, conductivity, and mechanical properties (Fig. 8e). It shows promising potential for integrated wearable sensors.[37–40]

Antimicrobial Properties of PPAS-Al^{3+} Gels

Because gel sensors need to be in contact with the skin to transmit strain signals accurately, antimicrobial ability is essential to protect the skin from bacterial invasion. The growth of *E. coli* and *S. aureus* on agar plates was observed to demonstrate the antimicrobial properties of the gel. Compared with PPA-Al^{3+}, the PPAS-Al^{3+} gel exhibited better antibacterial activity, and the addition of SBMA enhanced the inhibitory effect against *E. coli* (98.9%) and *S. aureus* (99.65%) (Figs. 9a and 9b). The zwitterionic PSBMA played an important role in antimicrobial performance because it could form a robust hydration layer that effectively resists electrostatic interactions between the material surface and biomolecules, suppressing bacterial adhesion. Moreover, the strong electrostatic attraction between the positive charge of SBMA and the negative components in the bacterial phospholipid membrane leads to bacterial inactivation through membrane disintegration.[14,41] The outstanding antibacterial properties of the PPAS-Al^{3+} gels effectively prevent microbial colonization on the sensor surface, thereby ensuring signal stability and long-term biocompatibility during wireless health monitoring. This feature is particularly crucial for continuous wearable applications where skin contact poses a risk of bacterial infection.

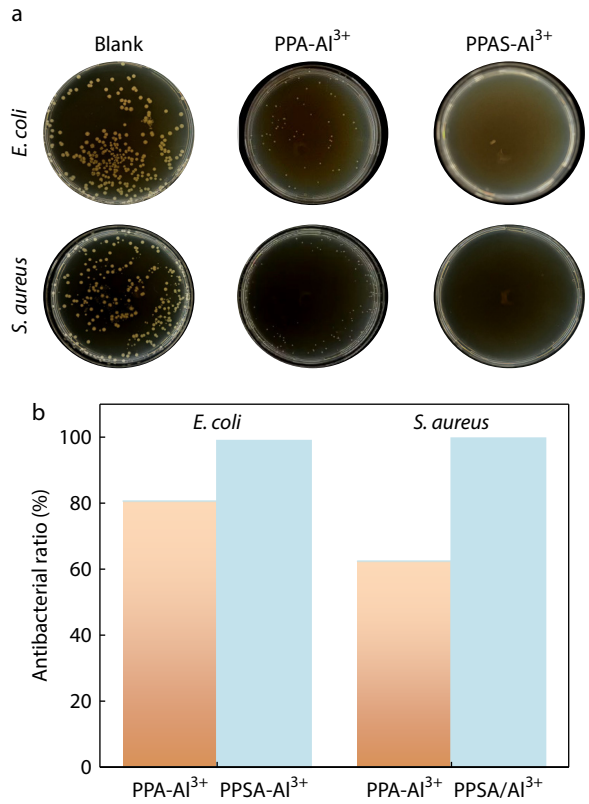

Fig. 9 (a) Acroscopic images of the antibacterial performance of PPA-Al^{3+} and PPAS-Al^{3+} gels and (b) lethality of the zwitterionic gels against *S. aureus* and *E. coli*.

CONCLUSIONS

Anti-swelling zwitterionic gels (PPAS-Al^{3+}) with conductivity, high stretchability, and antimicrobial properties were fabricated by irradiating a mixed solution of AA, SBMA, $AlCl_3$, and PVA with UV. The gel was integrated with a wireless Bluetooth system to construct the strain sensors. It can monitor human joint movement, speech recognition, and intelligent underwater writing. The PPAS-Al^{3+} gel exhibited maximum elongation at break (600%) and tensile strength (700 kPa). It displayed high sensitivity (GF=1.92) at 200%–400% strain, high cycling stability (400 times of 5% strain), and a wide response range (0%–400%). It maintained excellent anti-swelling properties after 15 days in water (11%) and showed stable swelling ratios in different solutions after 7 days of immersion. The tensile strength was maintained at 78% of its initial value (550 kPa) after 3 days of immersion in water and exhibited an electrical conductivity of 0.6 S/m. In addition, it demonstrated exceptional sensing capabilities, enabling it to accurately detect various human activities and perform wireless sensing underwater. Moreover, the gels exhibited antimicrobial capability, and the addition of SBMA enhanced the inhibitory effect against *E. coli* (98.9%) and *S. aureus* (99.65%), which is beneficial for potential biomedical applications. This work provides a comprehensive study on the fabrication of wireless sensors based on an anti-swelling gel used for wireless wearable sensors, underwater communication, speech recognition, intelligent writing, and healthcare.

Conflict of Interests

The authors declare no interest conflict.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Graphical Abstract

Anti-swelling Zwitterionic Gels with High Stretchability, Conductivity for Wireless Underwater Strain Sensing

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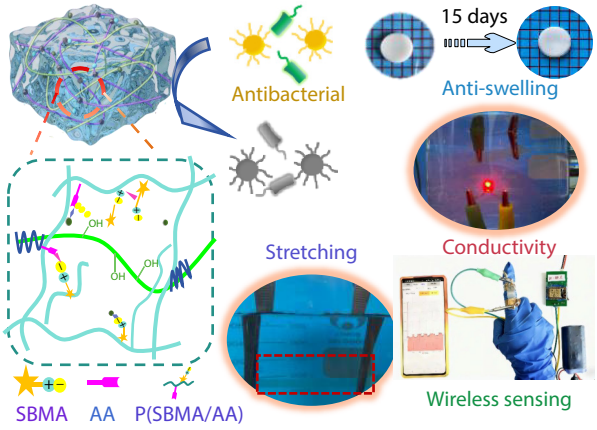
The PPAS-Al^{3+} zwitterionic gel exhibits excellent antibacterial and anti-swelling properties. It demonstrates high conductivity and stretchability, while its integrated wireless sensing system enables underwater motion monitoring, communication, and intelligent writing applications. The multi-functional anti-swelling zwitterionic gels provide a high-performance material platform for underwater wearable devices and soft robotics.



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