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Supporting Information for

A bioinspired deep-sea iontronic skin for underwater robotic tactile sensing

Qingyang Zheng¹, Daohui Zhang², Tianzhao Bu¹, Xin Fu², Naijia Xu², Shaoyu Liu¹, Sen Zhou¹, Bin Xie¹, Shuwen Chen³, Chwee Teck Lim^{4,7}, Changsheng Wu^{5,6,7,8*}, Hao Wu^{1,9*}.

1 Flexible Electronics Research Center, State Key Laboratory of Intelligent Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China.

2 State Key Laboratory of Robotics, Shenyang Institute of Automation, Institutes for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang, 110169, China.

3 Institute of Medical Equipment Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China.

4 Department of Biomedical Engineering, National University of Singapore, Singapore, 117583, Singapore.

5 Department of Materials Science and Engineering, National University of Singapore, Singapore, 117575, Singapore.

6 Department of Electrical and Computer Engineering, National University of Singapore, Singapore, 117583, Singapore.

7 Institute for Health Innovation and Technology, National University of Singapore, Singapore, 117599, Singapore.

8 The N.1 Institute for Health, National University of Singapore, Singapore, 117456, Singapore.

9 School of Integrated Circuits, Huazhong University of Science and Technology, Wuhan, 430074, China.

*Corresponding author. Email: cwu@nus.edu.sg; hwu16@hust.edu.cn

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Other Supplementary Material for this manuscript includes the following:

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Movie S2 (.mp4 format). Data glove collaborative control demonstration and non-destructive gripping of marine organisms.

Movie S3 (.mp4 fprmat). Underwater non-destructive gripping of paper cup with integrated deep-sea tactile sensors.

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Movie S5 (.mp4 fprmat). The state of underwater object grasping using a robotic manipulator.

Notes

Note S1. Theoretical modeling of porous ionogel structures

1-1. Porosity calculation of porous structures

The porosity φ_0 of the porous ionogel can be expressed as:

$$\varphi_0 = \frac{V_0 - V_1}{V_0} \times 100\% \quad (1)$$

Where, V_0 is the volume of the porous material in its natural state, and V_1 is the absolute dense state volume of the porous material. We employed the weighing method to determine the porosity of the porous ionic gels. This method calculates porosity based on the change in weight before and after submersion in water¹. The skeleton volume of the porous structure can be obtained from the density and dry weight of the ionic gel. Using this information, the porosity of the material can be calculated using the following formula:

$$\varphi_0 = \frac{V_2}{V_1 + V_2} \quad (2)$$
$$\varphi_0 = \frac{(m - m_{\text{PIG}}) / \rho_{\text{water}}}{m_{\text{PIG}} / \rho_{\text{PIG}} + (m - m_{\text{PIG}}) / \rho_{\text{water}}}$$

Where, m_{PIG} is the initial weight of the porous ionic gel, and m is the total mass of water inhaled by the same volume of porous ionic gel, ρ_{PIG} and ρ denote the densities of porous ionic gels and water, respectively.

1-2. Young's modulus calculation of porous ionogels

The dielectric layer of the tactile sensor is composed of a porous ionic gel. According to Ashby's equivalent theory², the equivalent Young's modulus of an open-pore ionic gel can be expressed as follows:

$$E_{\text{PIG}} = B \cdot E_{\text{IG}} \cdot (1 - \varphi_0)^2 \quad (3)$$

Where, E_{IG} is the Young's modulus of the base ionogel material, and B is a constant that includes all geometric features. The constant for highly porous materials can usually be expressed as $B \approx 1^2$.

1-3. Compression deformation analysis of porous ionogels

As a functional layer of the tactile sensor, the deformation of the porous ionogel directly influences the sensor's response. All pores within the structure are open, and the compression deformation of the sensor is calculated by considering the connectivity of these pores within the porous framework. The compressive strain ε of a porous ionic gel can be expressed as:

$$\varepsilon = \frac{\Delta t}{t_0} = \frac{F}{E_{\text{PIG}} A} = \frac{P}{E_{\text{PIG}}} \quad (4)$$

Where, t_0 is the initial thickness of the porous ionogel, Δt is the compression deformation thickness of the porous ionogel, A is the electrode area, and F is the contact force applied on the electrode.

Combining equation (3) and (4), the compression strain of the tactile sensor can be expressed as:

$$\varepsilon = \frac{P}{B \cdot E_{\text{IG}} \cdot (1 - \varphi_0)^2} \quad (5)$$

Note S2. Theoretical modeling of a bionic iontronic tactile sensor for underwater sensing

The equivalent circuit of an iontronic sensor operating in an aquatic environment can be divided into two parallel components: one part consists of a hydrophobic porous ionogel connected to an electrode, while the other part consists of seawater and the rest of the electrode. Due to their high ionic conductivity, both the ionogel and the seawater dielectric generate electric double layer (EDL) micro-capacitance at the upper and lower electrode layers. Assuming a uniform distribution of pores within the porous ionogel, we can represent the dielectric of the capacitive sensor as two branches, as illustrated in Figure.S3. The capacitance of the porous ionogel C_{EDL_PIG} and the capacitance of seawater in the pores $C_{EDL_seawater}$ are arranged in parallel.

In the i th column of the equivalent circuit, the equivalent circuit model for the capacitance of porous ionic gel C_{PIG} and the capacitance of seawater in the pores $C_{seawater}$ is expressed as³:

$$\begin{aligned} \frac{1}{Z_{sensor_i}} &= \frac{1}{Z_{PIG_i}} + \frac{1}{Z_{seawater_i}} \\ &= j\omega C_{PIG_i} + j\omega C_{seawater_i} \end{aligned} \quad (6)$$

Therefore, the capacitance of i th column can be expressed as:

$$\begin{aligned} C_{sensor_i} &= \frac{1}{\omega I_{mag}(Z_{sensor_i})} \\ &= C_{PIG_i} + C_{seawater_i} \end{aligned} \quad (7)$$

Assuming that the pores of the ionic gel are uniformly distributed, the contact area A_i of each column of the equivalent circuit with the electrodes can be expressed as:

$$A_i = \frac{A}{n} \quad (8)$$

Where, A is the total area of the electrodes, and n is the total number of branches of the equivalent circuit.

The capacitance of the porous ionic gel and seawater can be expressed as:

$$\begin{aligned}
C_{\text{PIG}_i} &= \frac{\varepsilon_{\text{PIG}} \cdot \varepsilon_0 \cdot A_{\text{PIG}_i}}{t_{\text{PIG}_i}} \\
C_{\text{seawater}_i} &= \frac{\varepsilon_{\text{seawater}} \cdot \varepsilon_0 \cdot A_{\text{seawater}_i}}{t_{\text{seawater}_i}}
\end{aligned} \tag{9}$$

Where, ε_{PIG} and $\varepsilon_{\text{seawater}}$ are the relative permittivity of porous ionic gels and seawater respectively, ε_0 is the vacuum dielectric constant, A_{PIG_i} and A_{seawater_i} are the contact areas of the i th column of ion gel and seawater with the electrodes respectively, t_{PIG_i} is the thickness of the i th column of porous ionic gel, and t_{seawater_i} is the thickness of the i th column of seawater between electrodes.

From the uniformly distribution of the pores of the porous ionogel:

$$\begin{aligned}
t_{\text{PIG}_1} &= t_{\text{PIG}_2} = \dots = t_{\text{PIG}_n} = t_{\text{PIG}} \\
A_{\text{PIG}_1} &= A_{\text{PIG}_2} = \dots = A_{\text{PIG}_n} = A_{\text{PIG}_i} \\
t_{\text{seawater}_1} &= t_{\text{seawater}_2} = \dots = t_{\text{seawater}_n} = t_{\text{seawater}} \\
A_{\text{seawater}_1} &= A_{\text{seawater}_2} = \dots = A_{\text{seawater}_n} = A_{\text{seawater}_i}
\end{aligned} \tag{10}$$

Equation (9) and (10) can be solved as:

$$\begin{cases} C_{\text{PIG}_1} = C_{\text{PIG}_2} = \dots = C_{\text{PIG}_n} = C_{\text{PIG}} \\ C_{\text{seawater}_1} = C_{\text{seawater}_2} = \dots = C_{\text{seawater}_n} = C_{\text{seawater}} \end{cases} \tag{11}$$

Combining equation (5), (7) and (11), the output capacitance of a porous iontronic sensor in an aquatic environment can be expressed as:

$$\begin{aligned}
C_{\text{sensor}} &= \sum_{i=1}^n (C_{\text{PIG}_i} + C_{\text{seawater}_i}) \\
&= n \left(\frac{\varepsilon_{\text{PIG}} \cdot \varepsilon_0 \cdot A_{\text{PIG}_i}}{t_{\text{PIG}}} + \frac{\varepsilon_{\text{seawater}} \cdot \varepsilon_0 \cdot A_{\text{seawater}_i}}{t_{\text{seawater}}} \right) \\
&= \frac{\varepsilon_{\text{PIG}} \cdot \varepsilon_0 \cdot A \cdot (1 - \varphi_0)}{t_{\text{PIG}}} + \frac{\varepsilon_{\text{seawater}} \cdot \varepsilon_0 \cdot A \cdot \varphi_0}{t_{\text{seawater}}}
\end{aligned} \tag{12}$$

Note S3. Theoretical modeling of equivalent contact force and capacitive response mechanism

From equation (5), the compressive strain of the porous ionic gel can be expressed as:

$$\varepsilon = \frac{P}{B \cdot E_{IG} \cdot (1 - \varphi_0)^2} \quad (13)$$

From equation (2), the porosity of the porous ionogel pair is denoted as φ_0 . The initial thickness t_{PIG0} of the ionogel and the initial thickness $t_{seawater0}$ of seawater within the pores are represented as follows:

$$t_{PIG0} = t_0 \cdot (1 - \varphi_0) \quad (14)$$

$$t_{seawater0} = t_0 \cdot \varphi_0 \quad (15)$$

Where, the thickness t is the initial spacing between the top and bottom electrodes. When $\varepsilon < \varphi_0$, the sensor response is calculated as the relative change in capacitance between the ionic gel and seawater during the pore closure phase. This measurement is essential for understanding the sensor's behavior in varying environmental conditions. At this stage, the thickness of the ionic gel is incompressible, i.e. $t_{IG} = t_{IG0}$. The nominal compressive strain of the tactile sensor can be expressed as follows:

$$\varepsilon = 1 - \frac{t_{PIG} + t_{seawater}}{t_0} \quad (16)$$

$$\begin{aligned} \varepsilon &= 1 - \frac{t_{PIG0}}{t_0} - \frac{t_{seawater}}{t_0} \\ \varepsilon &= \varphi_0 - \frac{t_{seawater}}{t_0} \end{aligned} \quad (17)$$

Combining equation (13) and (17), The variation $t_{seawater}$ of the seawater thickness between the electrodes can be expressed as follows:

$$t_{seawater} = t_0 \cdot \left(\varphi_0 - \frac{P}{B \cdot E_{IG} \cdot (1 - \varphi_0)^2} \right) \quad (18)$$

Thus, the contact force-response relationship for bionic porous tactile sensors utilized in aquatic environments can be described as follows:

$$C_{sensor} = \frac{\varepsilon_{PIG} \cdot \varepsilon_0 \cdot A}{t_0} + \frac{\varepsilon_{seawater} \cdot \varepsilon_0 \cdot A \cdot \varphi_0}{t_0 \cdot \left[\varphi_0 - \frac{P}{B \cdot E_{IG} \cdot (1 - \varphi_0)^2} \right]} \quad (19)$$

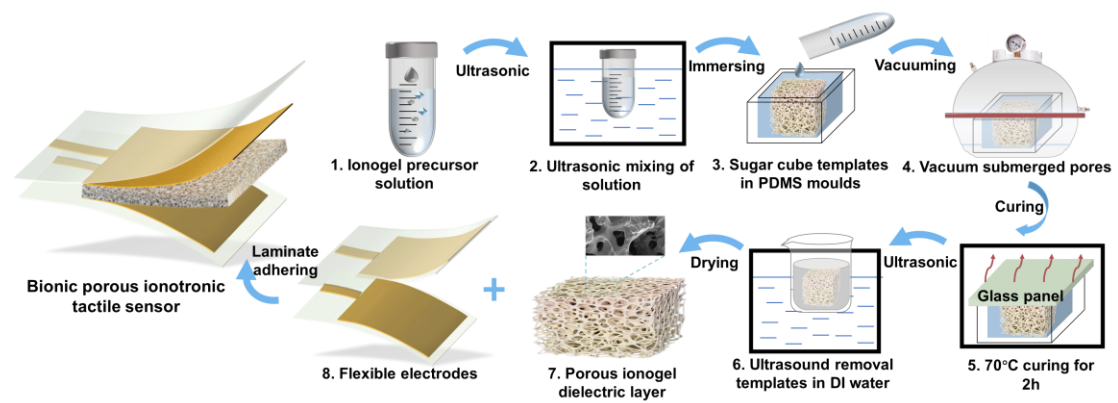


Figure S1. Schematic illustration of the preparation process for the iontronic tactile sensor with a bionic porous ionogel dielectric layer.

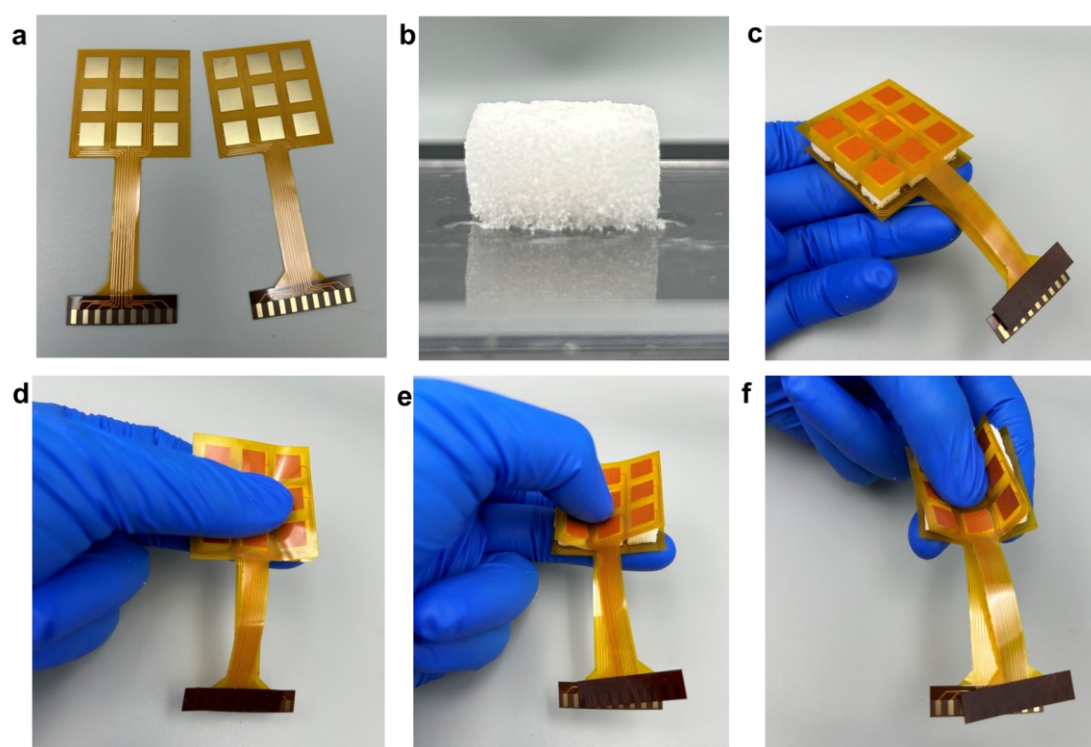


Figure S2. Digital photos of the major preparation steps and the sensor under different types of deformations. (a) Flexible electrodes. (b) Bionic porous ionogel dielectric layer. (c) Integrated deep-sea tactile sensor array. Bionic tactile sensor (d, e) compression (f) bending deformation.

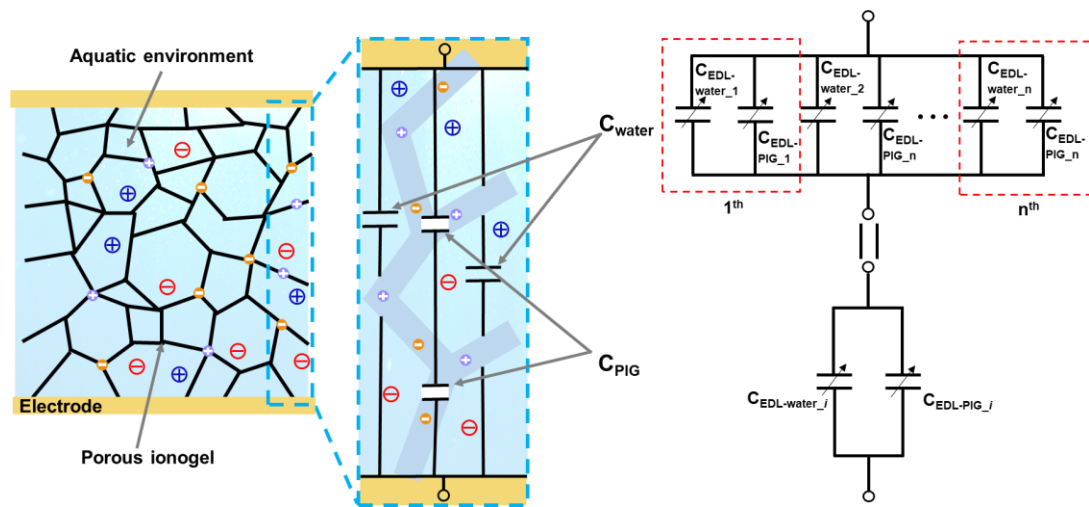


Figure S3. Simplified equivalent circuit model of iontronic tactile sensor with porous ionogel in aquatic environments.

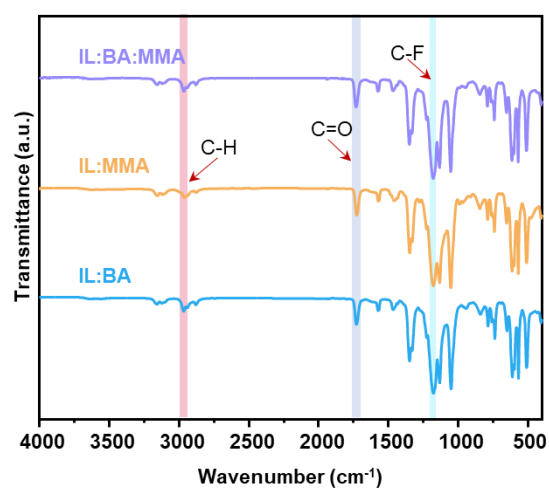


Figure S4. ATR-FTIR spectra of ionogels of different polymers. ATR-FTIR spectra of PBA, PMMA, PBA-co-MMA ionogels.

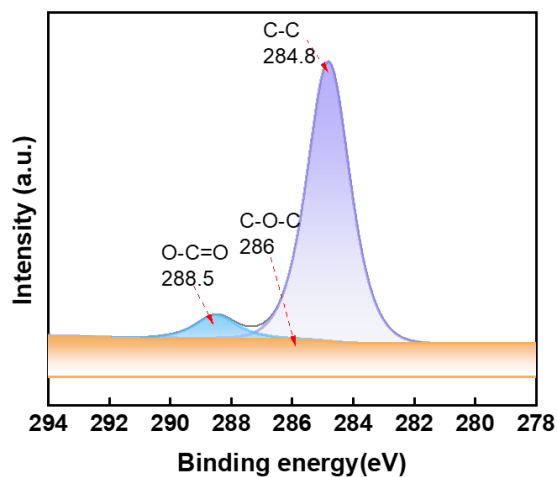


Figure S5. XPS survey (C1s) spectra of P([BMIM]TFSI-co-BA-co-MMA) ionogel.

In the XPS spectra, the characteristic peaks at 288.5 eV can be attributed to O-C=O and at 286 eV to C-O-C, further demonstrating the network compatibility of butyl acrylate with methyl methacrylate.

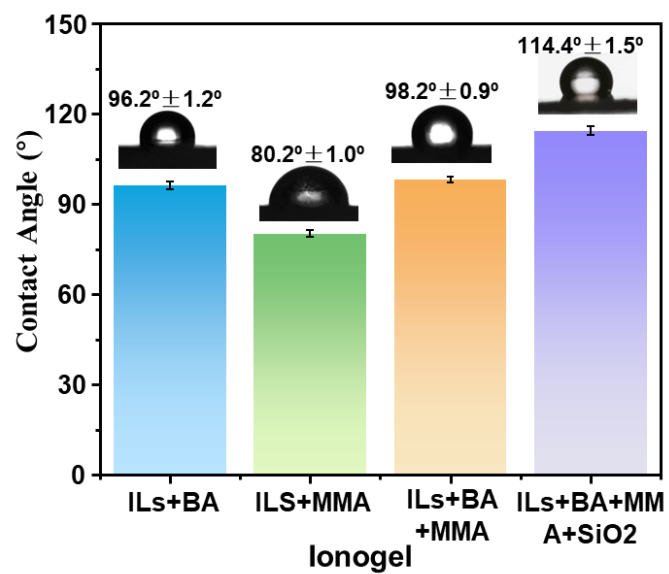


Figure S6. The water contact angle of ionogels prepared with different monomers.

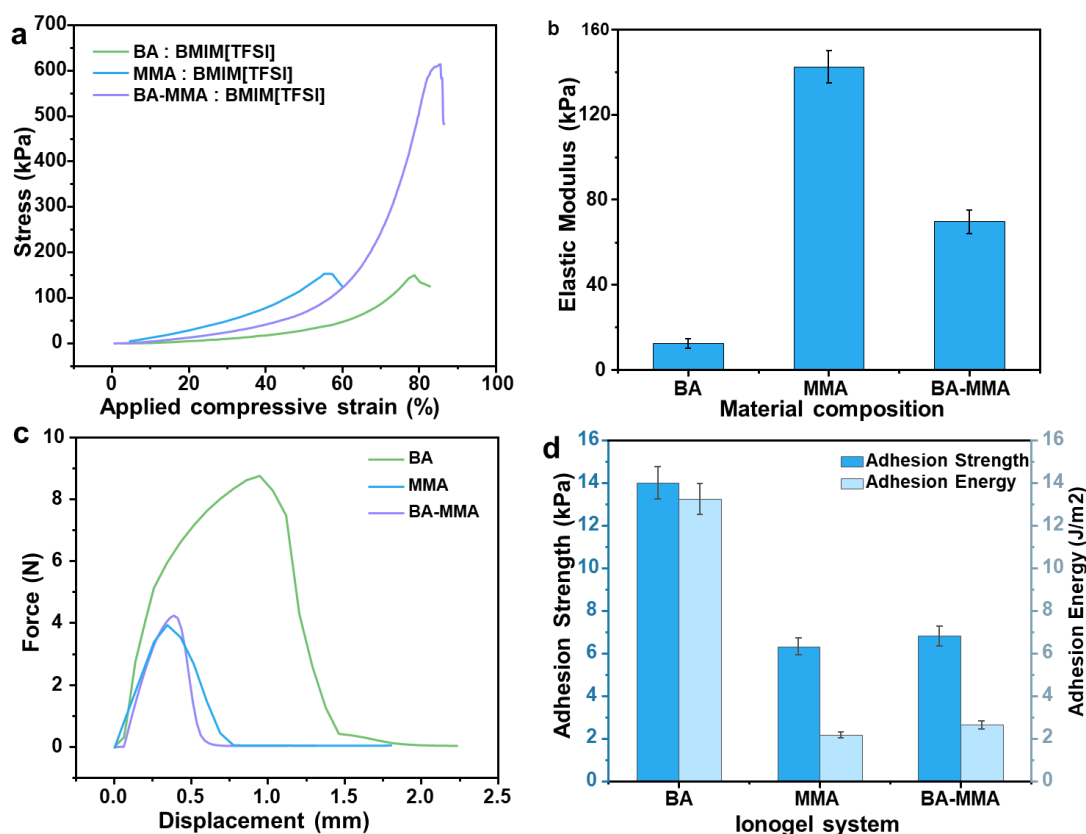


Figure S7. Mechanical properties of the ionogels with varying weight ratios of $w_{[ILs]}$: $w_{[BA]}$: $w_{[MMA]}$. The P([BMIM]TFSI-co-BA) is composed of [BMIM]TFSI and BA with a weight ratio of 8: 2. The P([BMIM]TFSI-co-MMA) is composed of [BMIM]TFSI and MMA with a weight ratio of 8: 2. The P([BMIM]TFSI-co-BA-r-MMA) is composed of [BMIM]TFSI and BA with a weight ratio of 8: 1.5: 0.5. (a) Uniaxial compression stress-strain curves of various weight ratios of $w_{[ILs]}$: $w_{[BA]}$: $w_{[MMA]}$. (b) The variations of Young's modulus with various weight ratios of $w_{[ILs]}$: $w_{[BA]}$: $w_{[MMA]}$. (c) Force-displacement curves measured by the adhesion test, and (g) adhesive strength and adhesive energy of ionogels with different weight ratios of $w_{[ILs]}$: $w_{[BA]}$: $w_{[MMA]}$. The figure demonstrates that P([BMIM]TFSI-co-BA-r-MMA) exhibits lower adhesion and elastic modulus. Consequently, the weight ratio was adjusted to 8:1.5:0.5 for the subsequent study. Data in (b) and (d) are presented as mean values $\pm$ SD, $n = 3$.

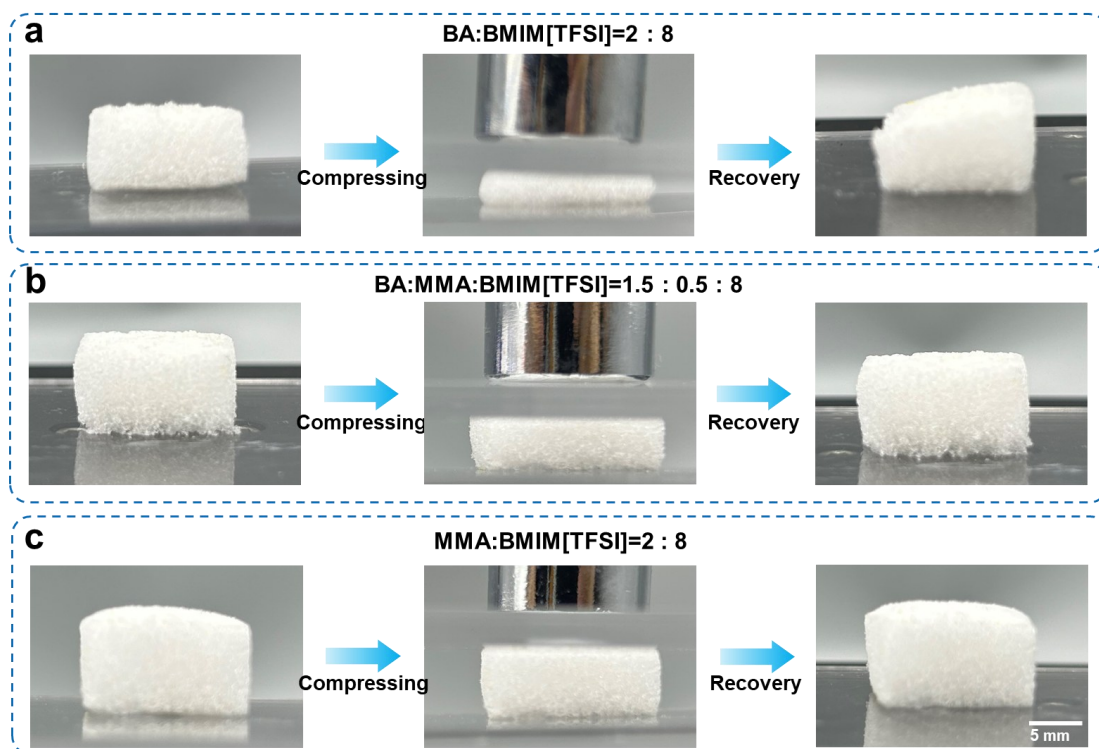


Figure S8. The images illustrate the compression deformation of the three porous ionogels before and after compression. Compared to Figure. a, the P([BMIM]TFSI-co-BA-r-MMA) porous ionogel demonstrates a quicker recovery time under the same load. Additionally, the deformation observed is greater than that shown in Figure. c.

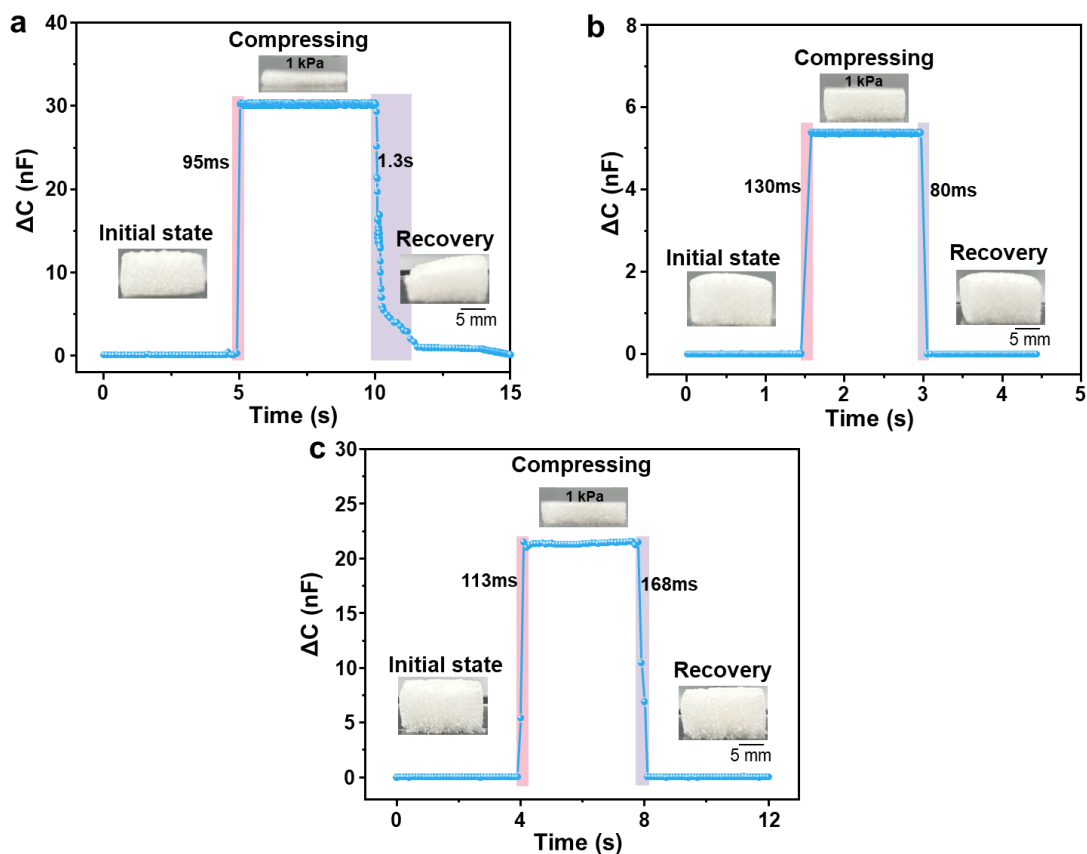


Figure S9. The response time for the three porous ionogel sensors prepared using the weight ratios shown in Figure S7. (a) The P([BMIM]TFSI-co-BA) iontronic sensor, with its lower elastic modulus, exhibits the quickest response; however, its high adhesion results in a recovery time of up to 1.3 seconds, making it unsuitable for repeated use. (b) In contrast, the P([BMIM]TFSI-co-MMA) iontronic sensor, characterized by a higher elastic modulus, shows a smaller response, leading to reduced sensitivity. (c) The P([BMIM]TFSI-co-BA-co-MMA) iontronic sensor demonstrates a moderate response and recovery time. Notably, all three sensors maintain the same structural dimensions, and the applied load during testing was 1 kPa.

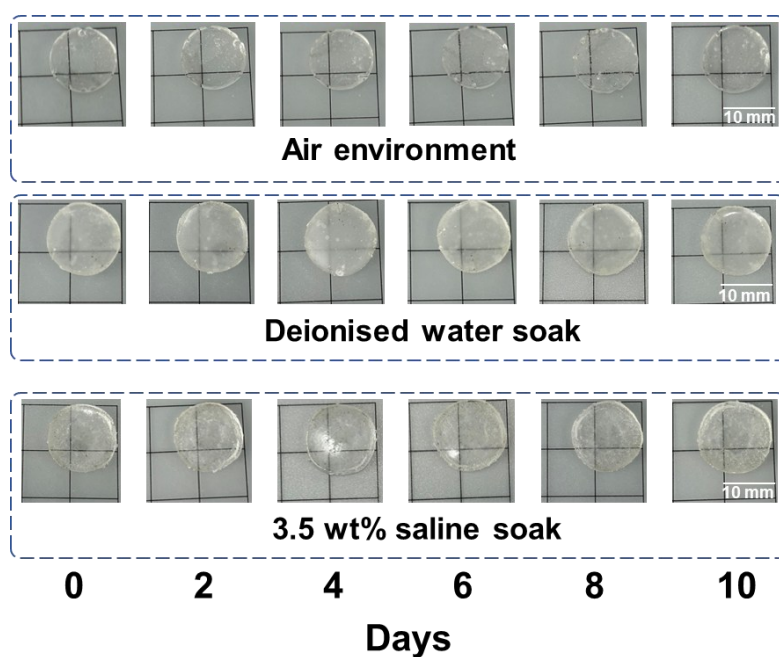


Figure S10. The swelling images of immersion in three aquatic environments. The swelling images depict 15 mm diameter and 2 mm high ionogel samples that were immersed for 10 days in three environments: air, deionized water, and a 3.5 wt% NaCl saline solution. The background grid used for reference has a side length of 10 mm. The ionogel samples are composed of [BMIM]TFSI, BA and MMA with a weight ratio of 8: 1.5: 0.5. The results indicate that the ionic gel did not exhibit swelling when immersed in any of the three environments tested.

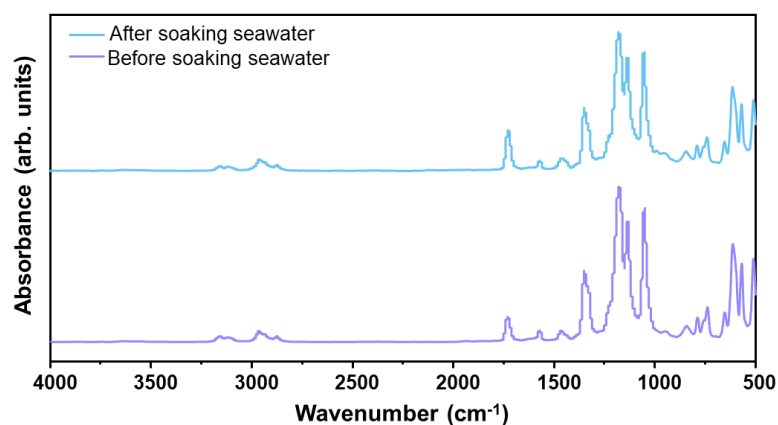


Figure S11. FTIR analysis of chemical bond in ionogel before and after 10 days immersion in 3.5 wt% NaCl solution. FTIR analysis reveals negligible changes in the cross-linking bonds of the ionogel after soaking in saline for 10 days, indicating that the stable network structure contributes to the durability of the material underwater.

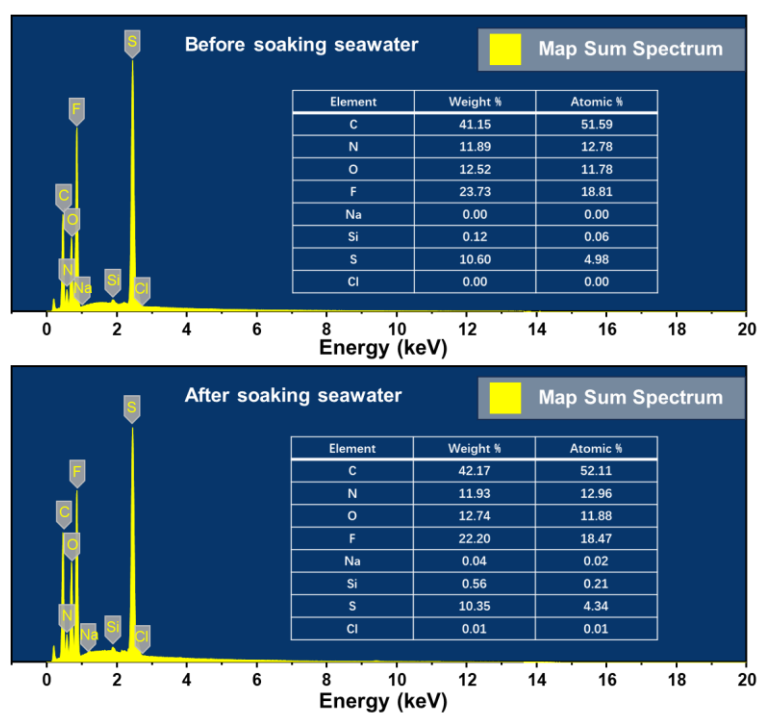


Figure S12. EDS Mapping analysis of ionogel elements before and after 10 days immersion in 3.5 wt% NaCl solution. Energy-dispersive X-ray spectroscopy (EDS) mapping results indicate roughly no Na^+ and Cl^- penetration into the ionogel after 10 days of soaking in saline.

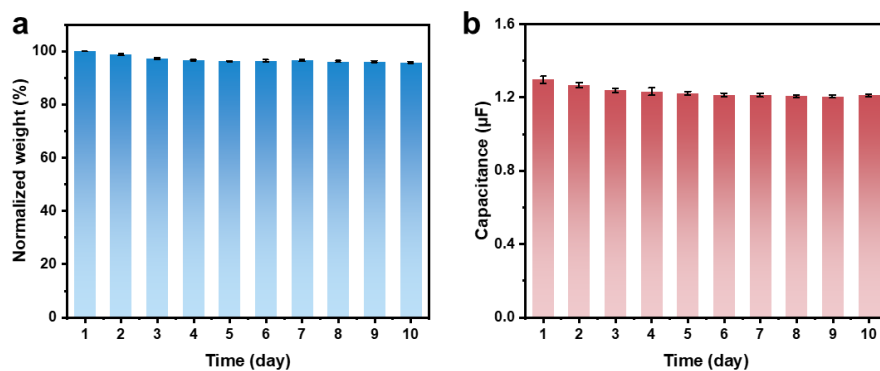


Figure S13. Effect of natural seawater ions (Na^+ , Mg^{2+} , SO_4^{2-} , Cl^- , etc.) on the performance of the ionogel. (a) Swelling rate variation of the ionogel after immersion in natural seawater. (b) Capacitance variation of the ionogel after immersion in natural seawater. The ionogel's swelling ratio reached equilibrium after 3 days of immersion in natural seawater, with negligible further changes. Its capacitance also stabilized after 3 days, with a fluctuation of $<3\%$ in the subsequent 8 days (total 11 days of immersion).

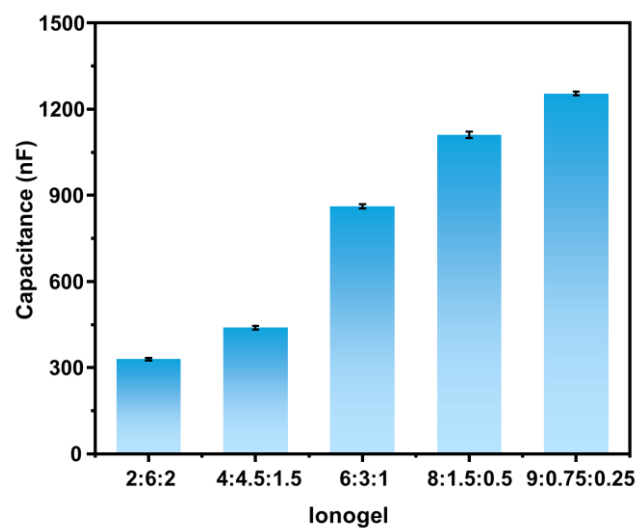


Figure S14. Electrical properties of the P([BMIM]TFSI-co-BA-co-MMA) with varying weight ratios of $w_{[ILs]}$: $w_{[BA]}$: $w_{[MMA]}$. With the increase in the proportion of ionic liquid, the initial capacitance of the ionogel increases significantly.

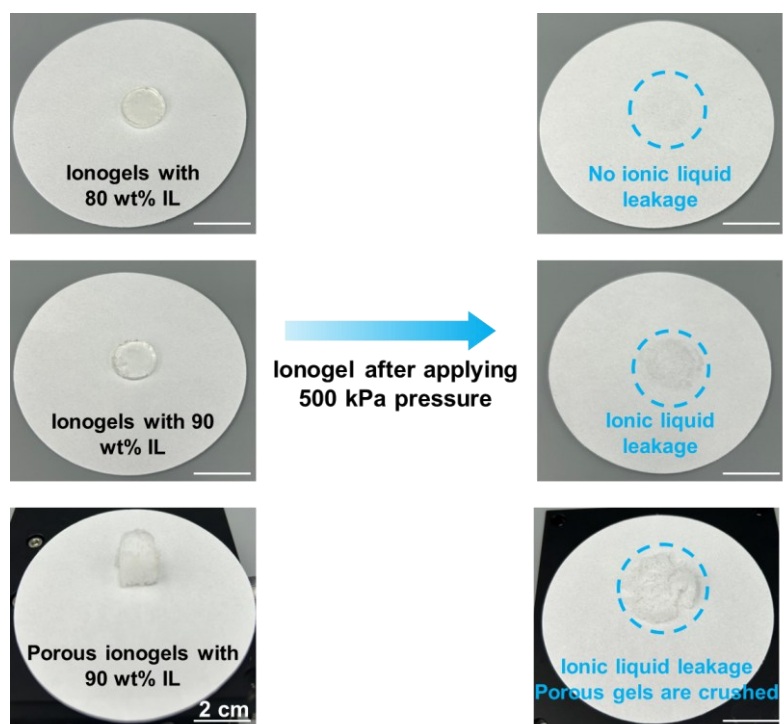


Figure S15. Ionic liquid leakage test from ionic gels polymerized with different weight ratios of [BMIM]TFSI when subjected to applied external pressure. The ionogel synthesized with 90 wt% ionic liquid exhibits the poorest mechanical strength, leading to cracking and ionic liquid leakage.

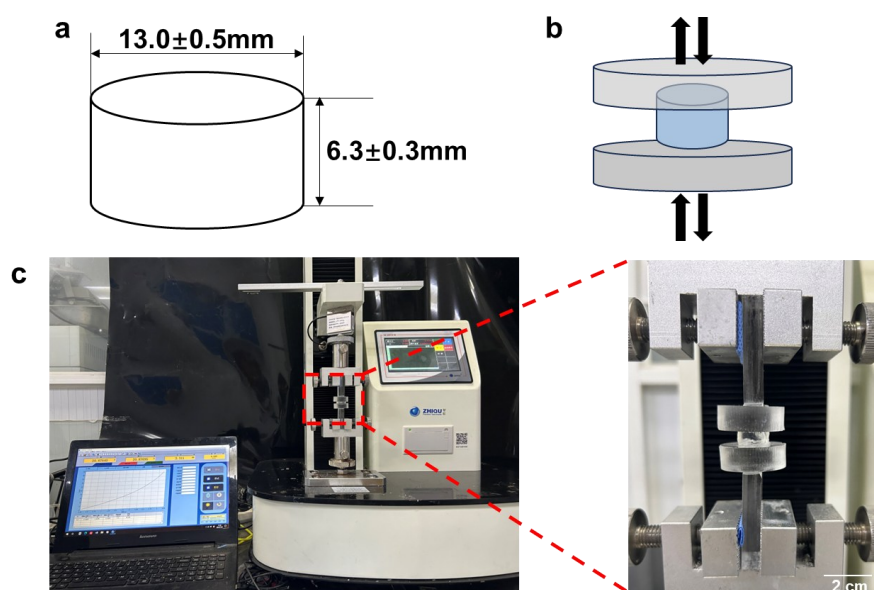


Figure S16. The images illustrate the mechanical performance test samples and the testing platform used in the experiments. (a) The dimensions of the uniaxial compression sample. (b) The loading mode employed during the uniaxial compression experiment. (c) Additionally, a schematic of the multifunctional loading platform used in the uniaxial compression experiment is presented, with insets highlighting specific loading details.

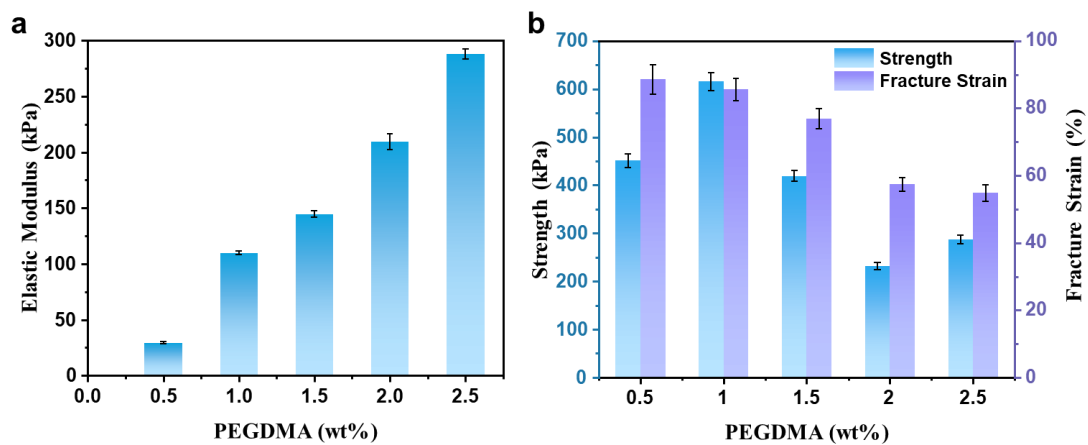


Figure S17. Mechanical properties of hydrophobic ionogels. (a) Young's modulus, and (b) strength and fracture strain of ionogels with various crosslink densities. Data in (a) and (b) are presented as mean values $\pm$ SD, $n = 3$.

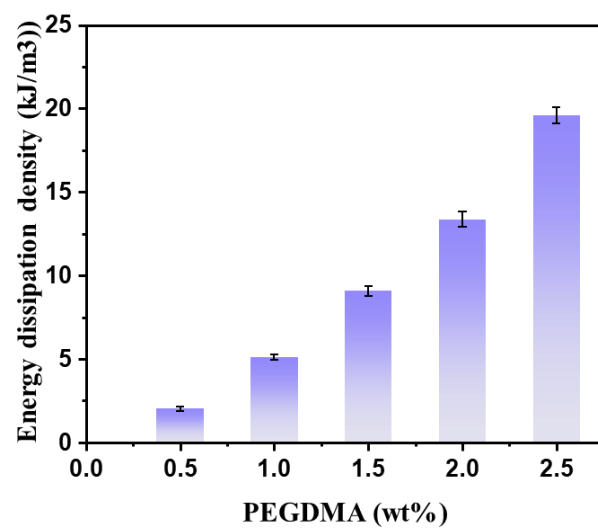


Figure S18. Density of energy dissipation with crosslink density of hydrophobic ionogels.

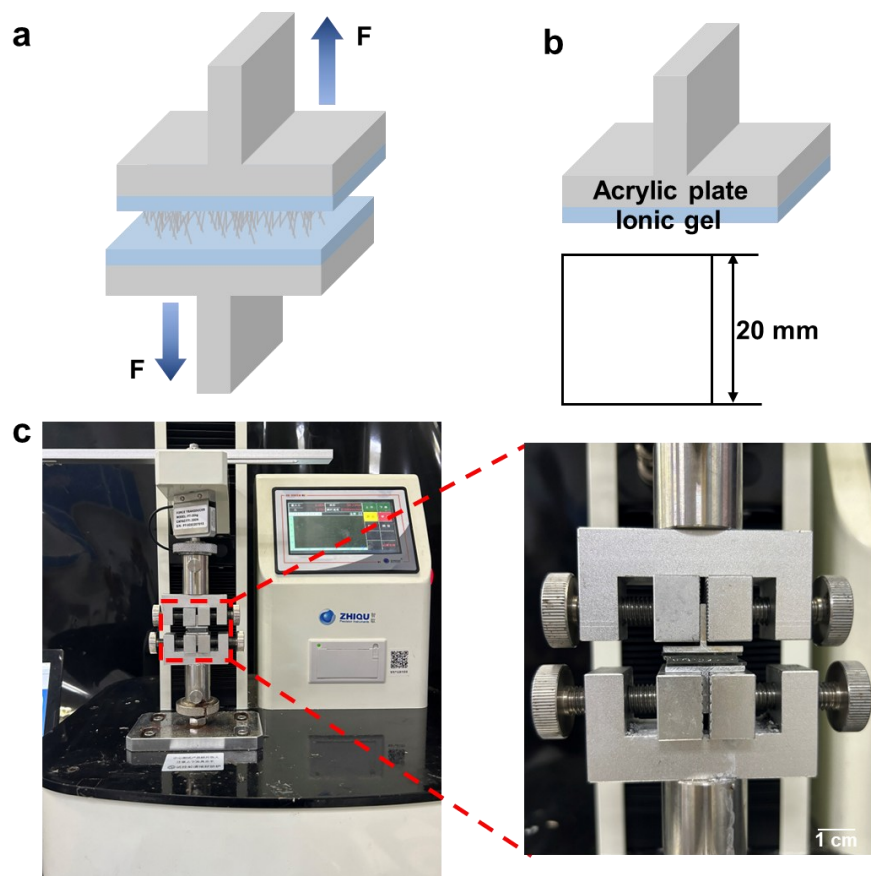


Figure S19. The images presenting experimental conditions during adhesion tests of ionogels. (a) The loading method for the adhesion experiment and the arrangement of the ionogel samples. (b) The dimensions of the ionogel sample utilized in the adhesion tests. (c) Additionally, a schematic of the multifunctional loading platform used in the adhesion experiment is shown, with insets highlighting specific details of the adhesion setup.

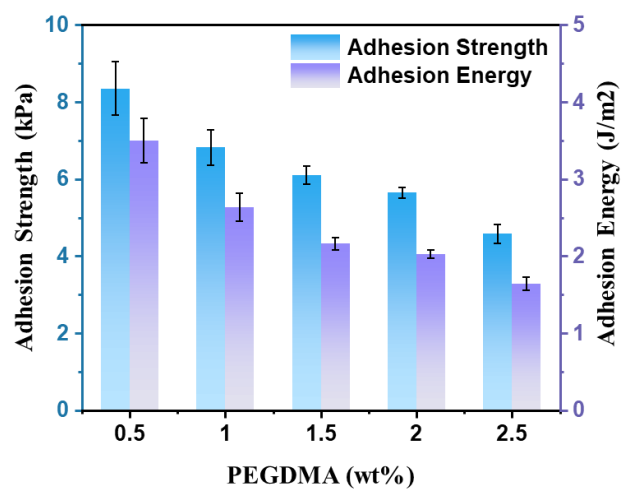


Figure S20. Adhesive strength and adhesive energy of ionogels with different crosslink density.

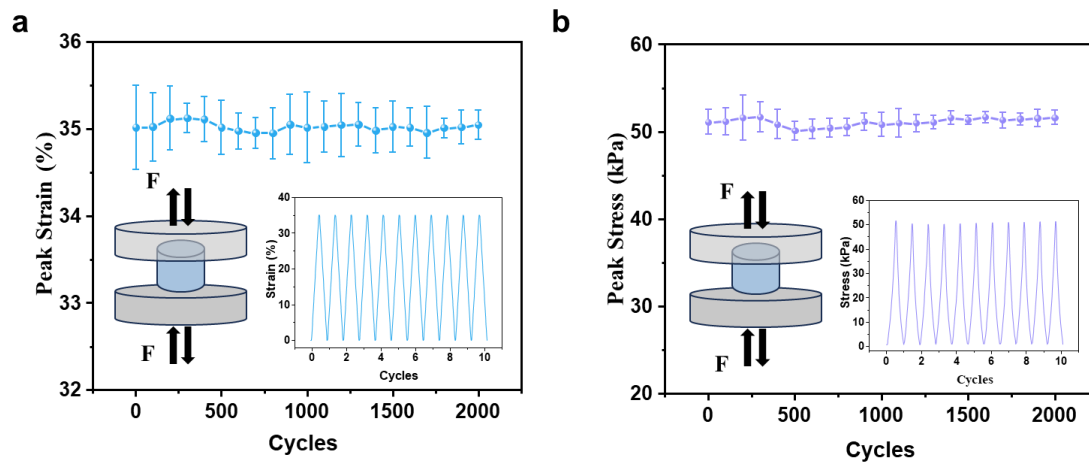


Figure S21. Mechanical properties of ionogels with 1 wt% crosslink density. (a) Peak strain and cycling curves, and (b) peak stress and cycling curves of 1.0 wt% crosslinked density ionogels. Data in (a) and (b) are presented as mean values $\pm$ SD, $n = 3$.

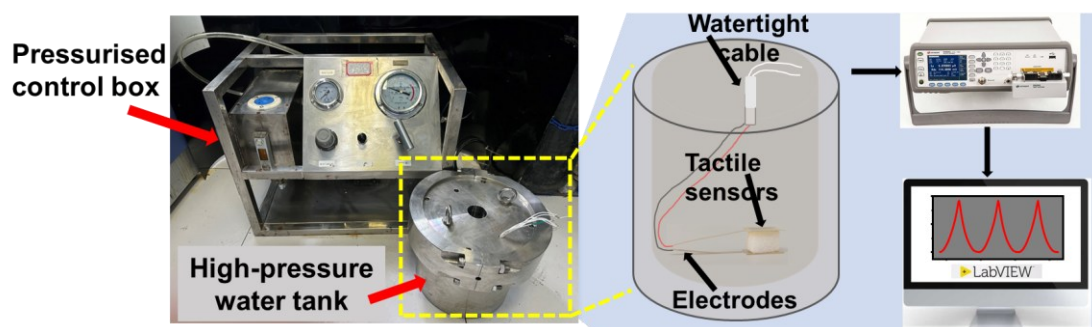


Figure S22. The schematic diagram illustrates a small laboratory pressure tank designed to simulate a hydrostatic environment. This pressure tank can achieve maximum pressures of up to 20 MPa, equivalent to a submerged depth of approximately 2000 meters. The inset highlights the arrangement of the bionic tactile sensor and the device used for real-time acquisition of sensing signals, connected via watertight cable.

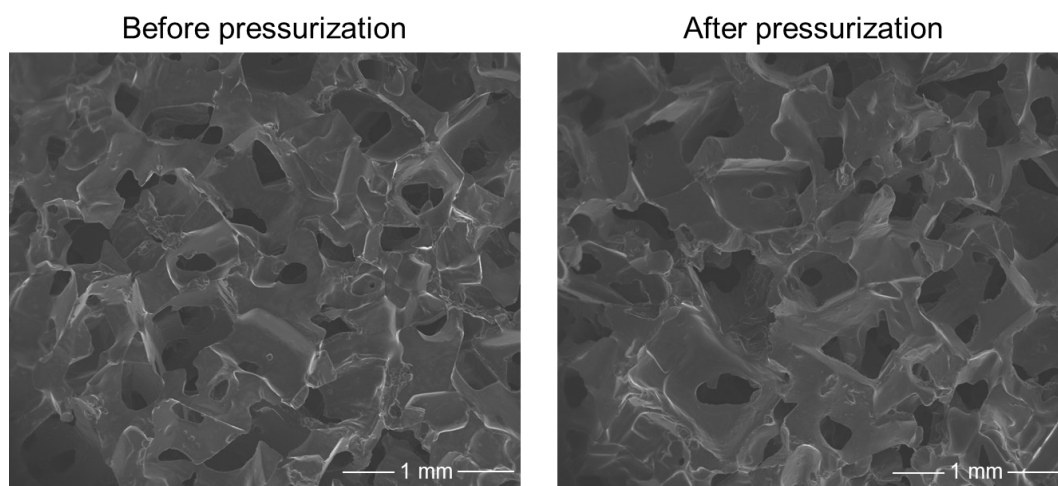


Figure S23. Cross-sectional micrographs of the porous ionogel before and after hydrostatic pressure loading. The microstructural images were obtained from the porous ionogel after being subjected to 50 MPa seawater pressure for 12 hours, with comparative images taken before pressure application. The comparison demonstrates that the pores and skeleton structure of the porous ionogel showed almost negligible collapse or deformation before and after pressure loading, confirming that negligible structural damage occurred in the porous ionogel under high-pressure seawater conditions.

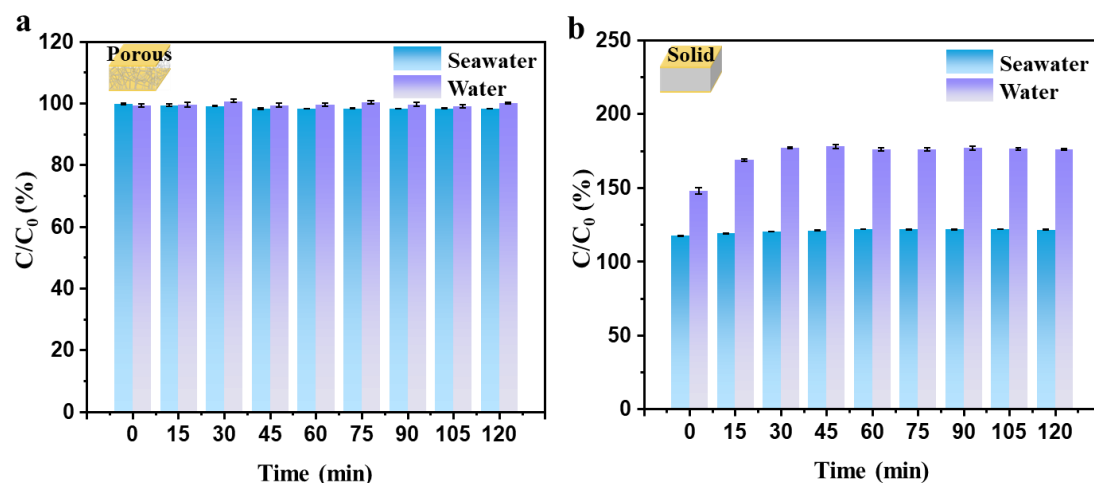


Figure S24. Hydrostatic pressure response of porous and solid tactile sensors. The schematic illustrates (a) the porous ionogel sensor and (b) the solid ionogel sensor, showing the relative capacitance change over time at 50 MPa hydrostatic pressure. Figure (a) indicates that the response signal of the porous sensor remains essentially constant over time at this pressure. In contrast, the solid sensors exhibit fluctuating responses. Data in (a) and (b) are presented as mean values $\pm$ SD, $n = 3$.

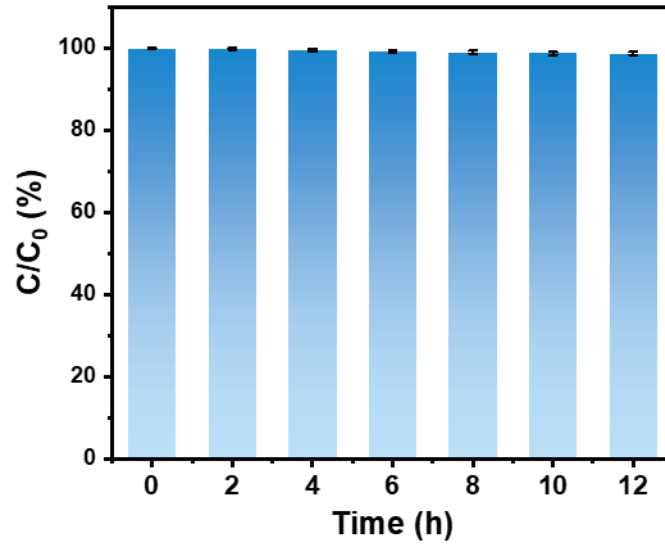


Figure S25. Durability test of the deep-sea tactile sensor under hydrostatic pressure. The tactile sensor was immersed in seawater within a pressure chamber, maintained at a constant hydrostatic pressure of 50 MPa for a continuous 12-hour pressure-holding test. The sensor's capacitance signal remained nearly constant throughout the 12-hour test, with a fluctuation of less than 1.5%. This 12-hour stable performance is sufficient to cover the duration of typical sea trial tasks, including the entire process of diving, underwater operation, and resurfacing.

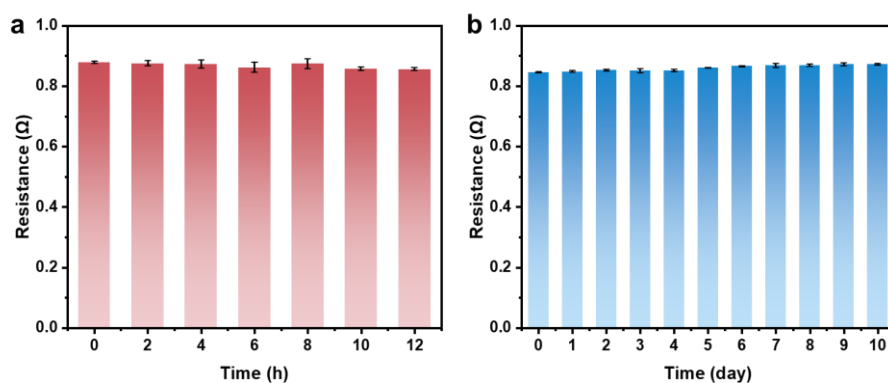


Figure S26. Stability of FPCB electrodes under hydrostatic pressure. (a) Resistance variation of the electrode under hydrostatic pressure. (b) Resistance variation of the electrode after immersion in seawater. The resistance of the electrodes remained stable throughout the 12-hour hydrostatic pressure test, with negligible further fluctuation. This directly indicates that the electrodes did not crack or experience structural damage under hydrostatic pressure. The FPCB was immersed in natural seawater for 10 days, the electrode resistance (monitored daily via a precision multimeter) was stably maintained at $\sim 0.86 \pm 0.05 \Omega$, with negligible changes in conductivity by oxidation.

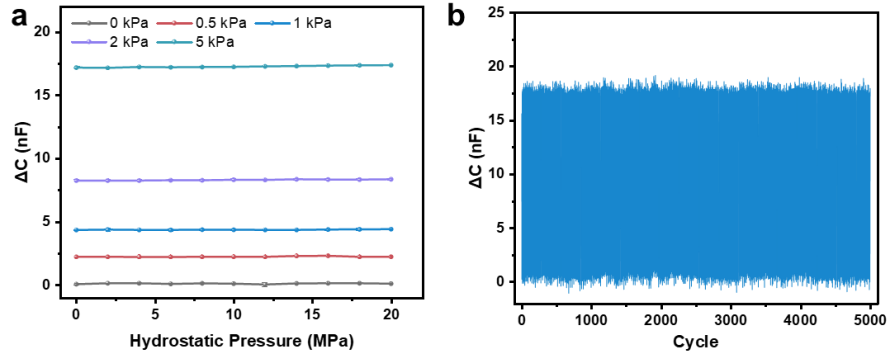


Figure S27. Sensing stability of the deep-sea tactile sensor in natural seawater. (a) Hydrostatic pressure response of the sensor under different loads in a natural seawater environment. (b) Cyclic curves of the sensor in natural seawater. The capacitance fluctuation of the sensor was less than 1% with the increase of hydrostatic pressure under all tested load conditions. The sensor's capacitance response remained stable throughout 5000 cycles, with negligible signal drift or decay. This result confirms that the high-pressure natural seawater environment does not cause significant interference with the sensor's contact force sensing performance.

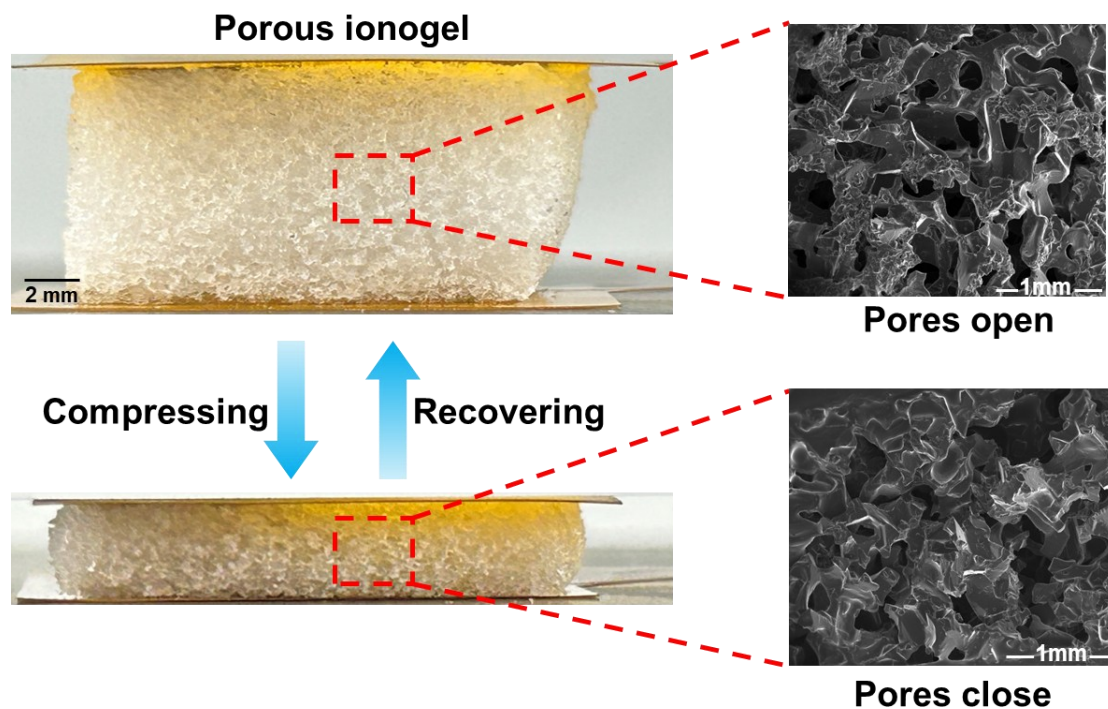


Figure S28. The optical images and scanning electron microscope schematic illustrate the compression and release process of the porous iontronic sensor. These images clearly demonstrate the closure of the pores under applied pressure, highlighting the structural changes that occur during the compression.

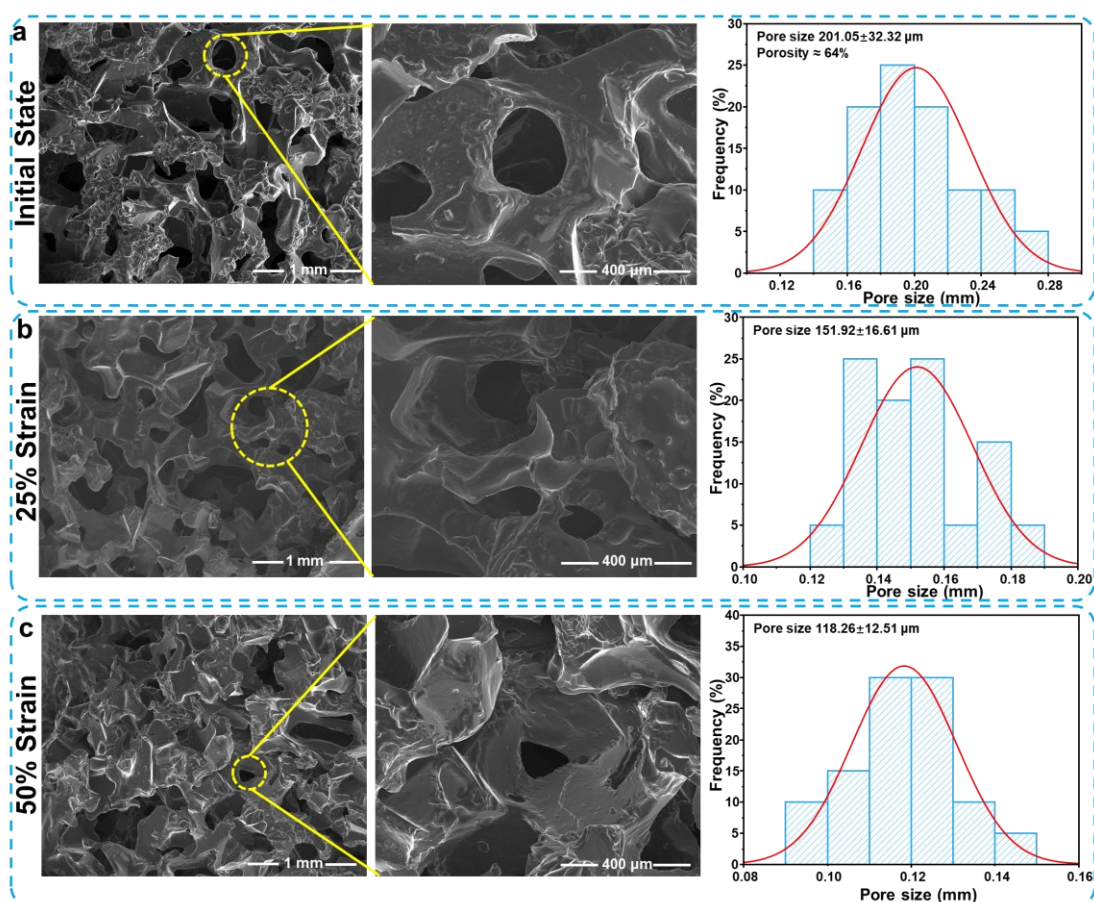


Figure S29. The scanning electron microscope (SEM) images and statistical pore sizes of porous iontronic sensors at various compressive strains. The pore SEM images and the statistical analysis of the porous structure of the porous ionogels are shown for three conditions: (a) the unstressed initial state, (b) the 25% compressive strain, and (c) the 50% compressive strain. These observations allow for a clear visualization of the changes in pore size and skeleton structure as a function of compressive strain.

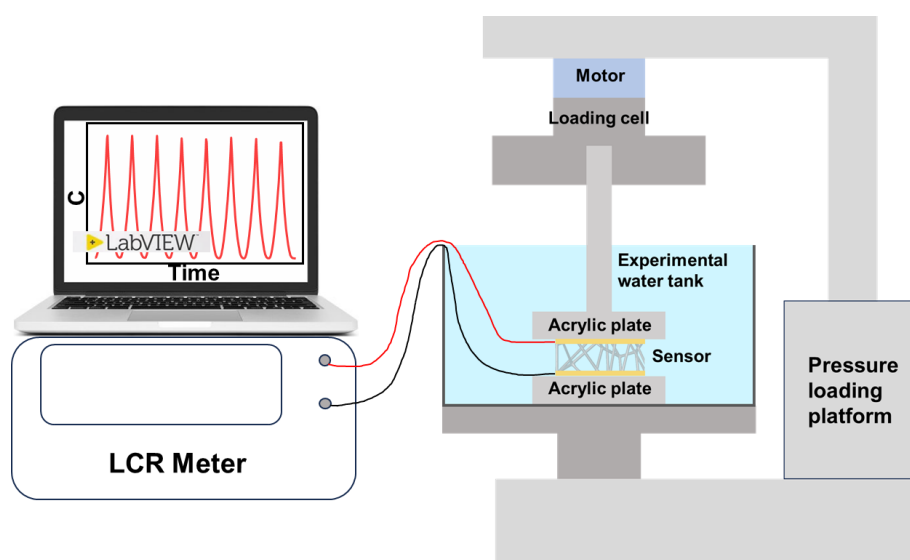


Figure S30. Schematic diagram of the experimental platform for testing tactile sensor performance in an aquatic environment.

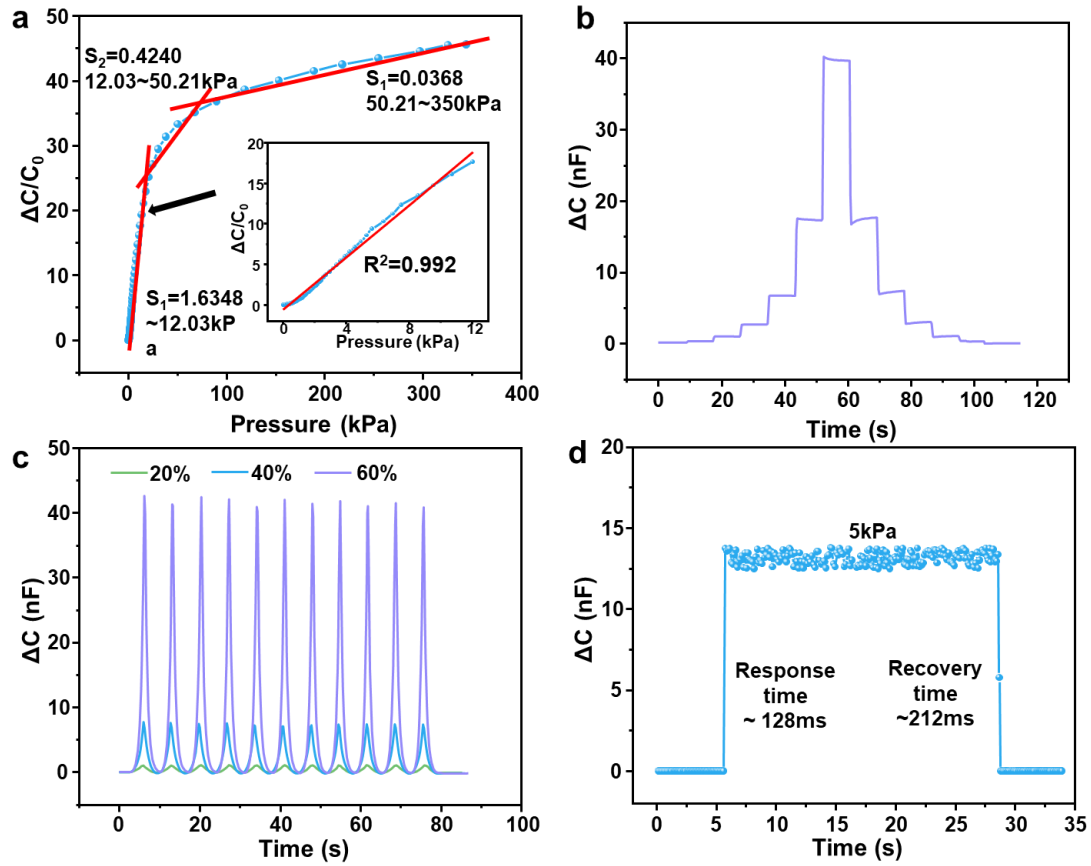


Figure S31. Sensing properties of the bionic iontronic tactile sensor in air environments. (a) The normalized change in capacitance as a function of the pressure of the tactile sensor. The figure directly shows the sensitivity of the sensor and the inset show the linearity of capacitance changes at the first stage pressure. (b) Stepped loading and unloading curves of flexible tactile sensor with different pressures. (c) Repeatability curves of capacitive response of the tactile sensor at various pressures (20%, 40%, and 60% strain). (d) Response and recovery time of tactile sensor at 5kPa pressures.

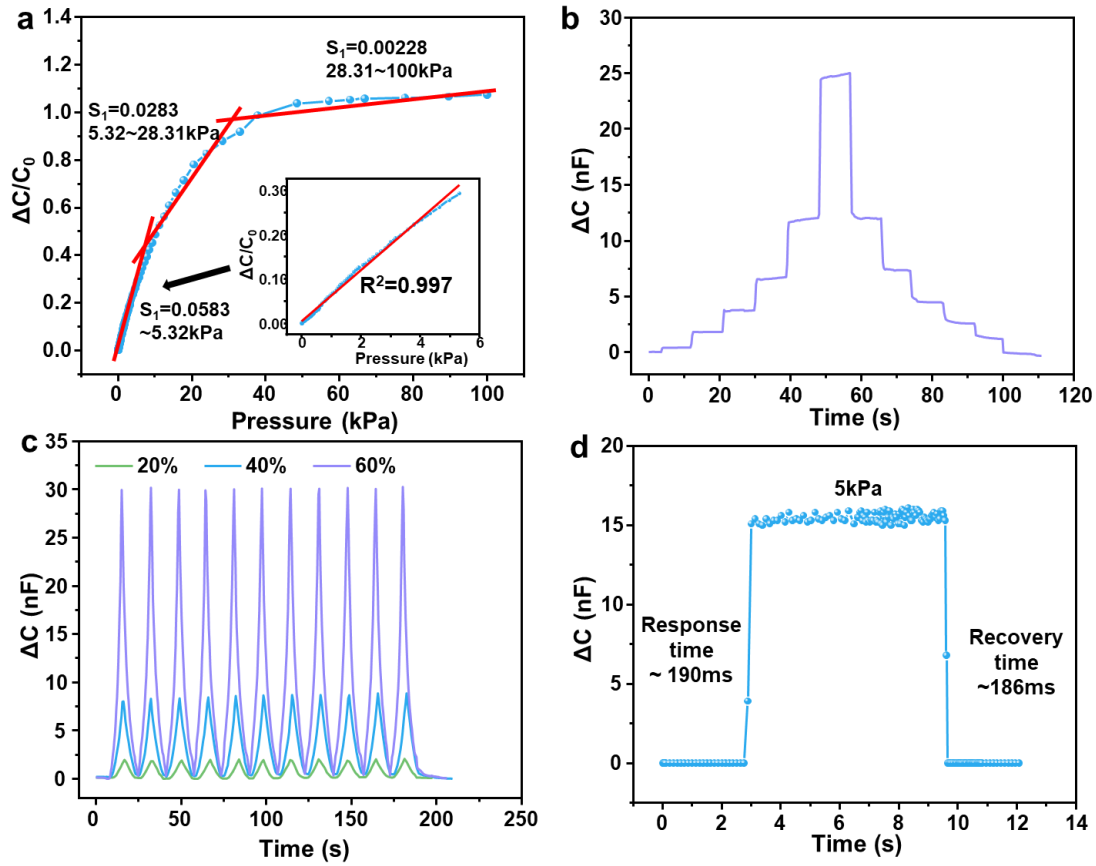


Figure S32. Sensing properties of the bionic iontronic tactile sensor in 3.5 wt% NaCl saline environments. (a) The normalized change in capacitance as a function of the pressure of the tactile sensor. The figure directly shows the sensitivity of the sensor and the inset show the linearity of capacitance changes at the first stage pressure. (b) Stepped loading and unloading curves of flexible tactile sensor with different pressures. (c) Repeatability curves of capacitive response of the tactile sensor at various pressures (20%, 40%, and 60% strain). (d) Response and recovery time of tactile sensor at 5kPa pressures.

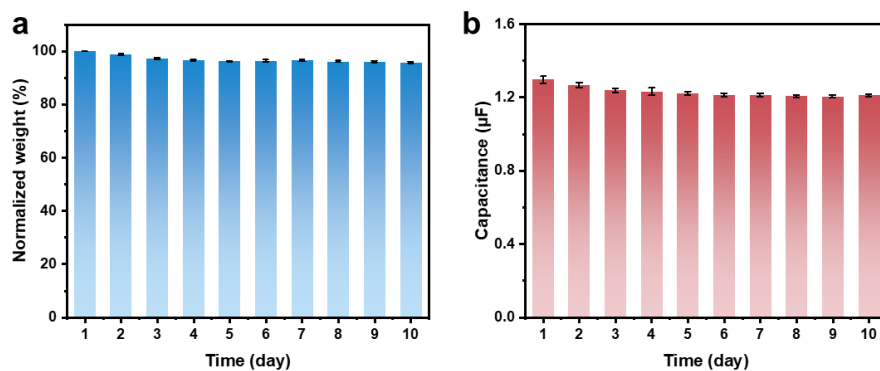


Figure S33. Effect of natural seawater ions (Na^+ , Mg^{2+} , SO_4^{2-} , Cl^- , etc.) on the performance of the ionogel. (a) Swelling rate variation of the ionogel after immersion in natural seawater. (b) Capacitance variation of the ionogel after immersion in natural seawater. The ionogel's swelling ratio reached equilibrium after 3 days of immersion in natural seawater, with negligible further changes. Its capacitance also stabilized after 3 days, with a fluctuation of $<3\%$ in the subsequent 8 days (total 11 days of immersion).

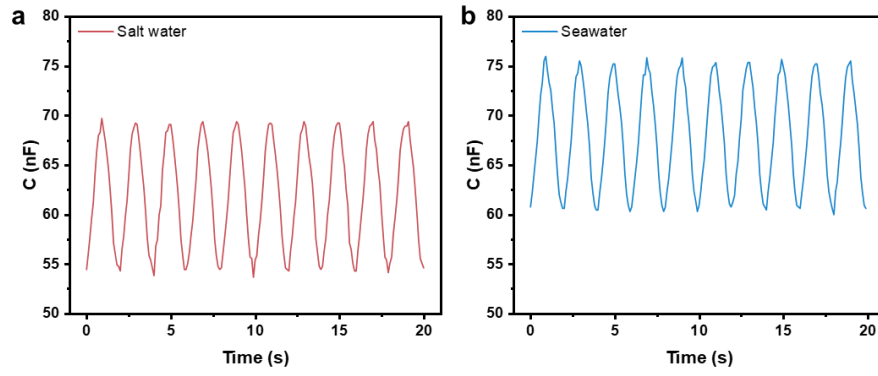


Figure S34. Influence of saltwater and seawater on sensor performance. (a) Cyclic loading response of the sensor in saltwater. (b) Cyclic loading response of the sensor in seawater. The environmental relative permittivity $\epsilon_{\text{seawater}}$ (Formula 3) of different solutions only affect the measured capacitance of the sensor, while they have no impact on the sensor's contact force detection in a single solution.

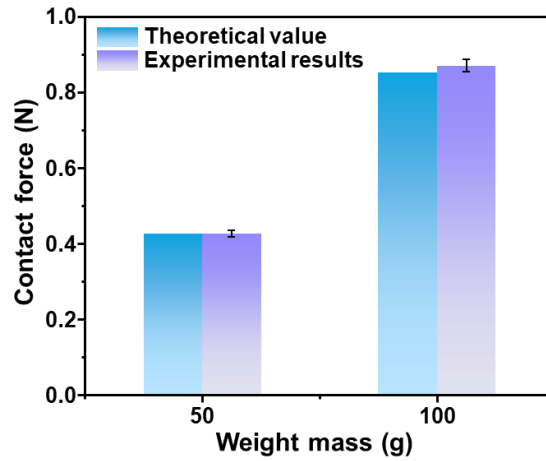


Figure S35. Theoretical and experimental results comparing the contact force exerted by different weights. For the 50 g weight, the gravity is 0.49 N, while the buoyancy in water is 0.0637 N, resulting in an applied contact force of 0.4263 N. In the case of the 100 g weight, the gravity is 0.98 N, and the buoyancy is 0.1274 N, yielding an applied contact force of 0.8526 N. The experimental errors for the 50 g and 100 g weights are 0.60% and 1.82%, respectively. These results confirm the accuracy of deep-sea tactile sensors in detecting contact forces.

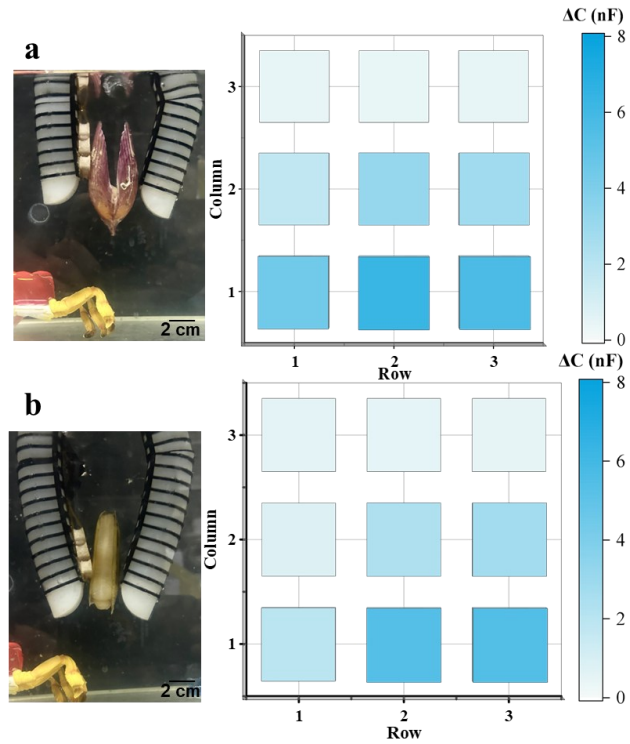


Figure S36. Soft gripper with integrated deep-sea tactile sensors gripping marine organisms. Mapped pressure distributions of (a) scallop, and (b) razor clam grasped by tactile sensors integrated in a soft gripper.

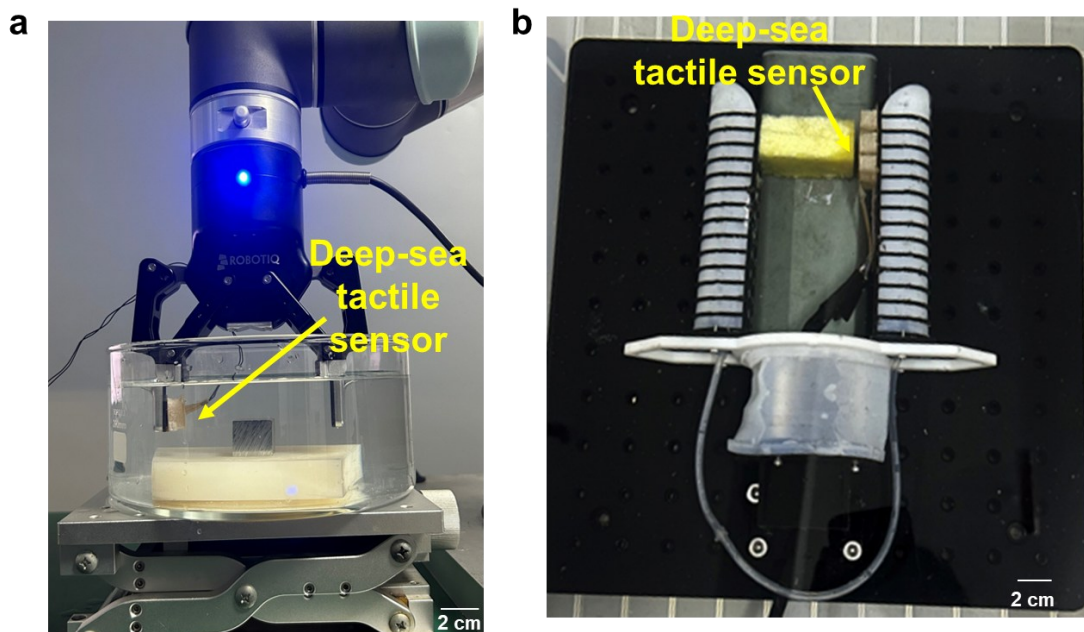


Figure S37. Robotic systems with integrated deep-sea tactile sensors. (a) Two-finger robotic sensing system. (b) Soft manipulator with integrated array sensors for gripping applications.

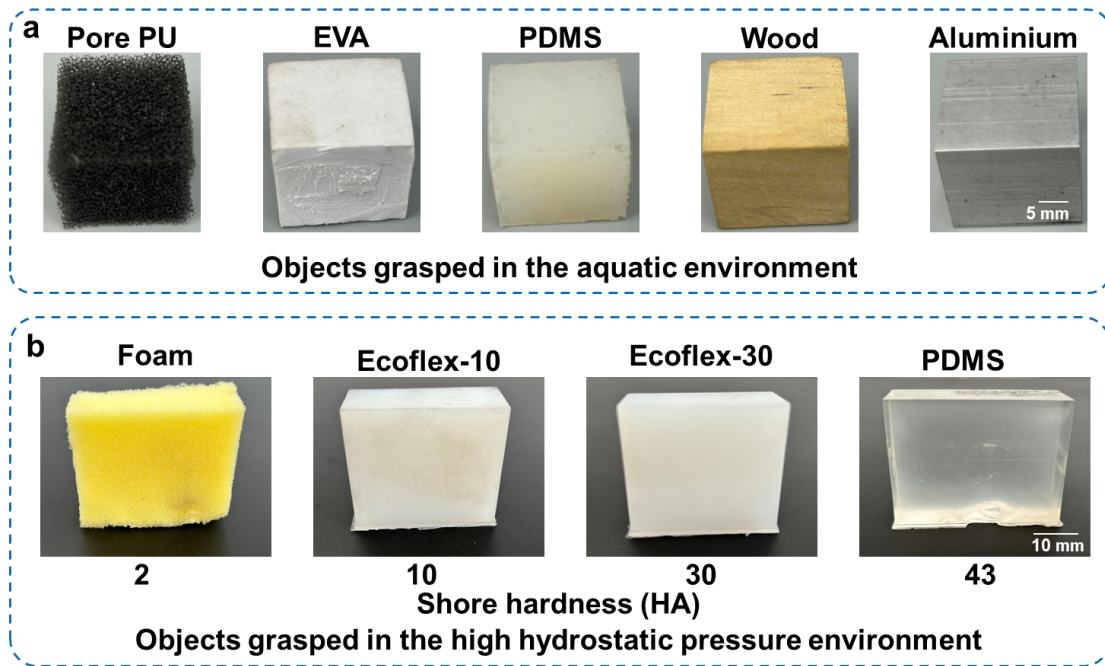


Figure S38. Objects of different hardness for grasp recognition applications. (a) and (b) Samples for different hardnesses.

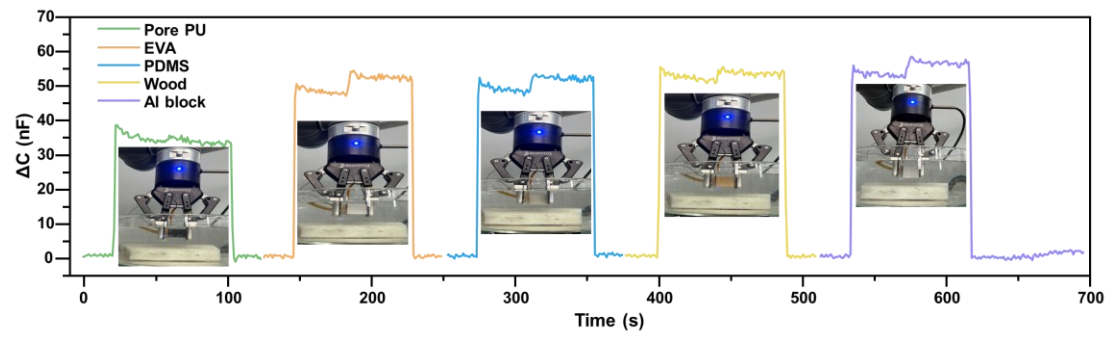


Figure S39. Response of a manipulator integrated with a flexible tactile sensor to grasp objects of different hardness in an aquatic environment.

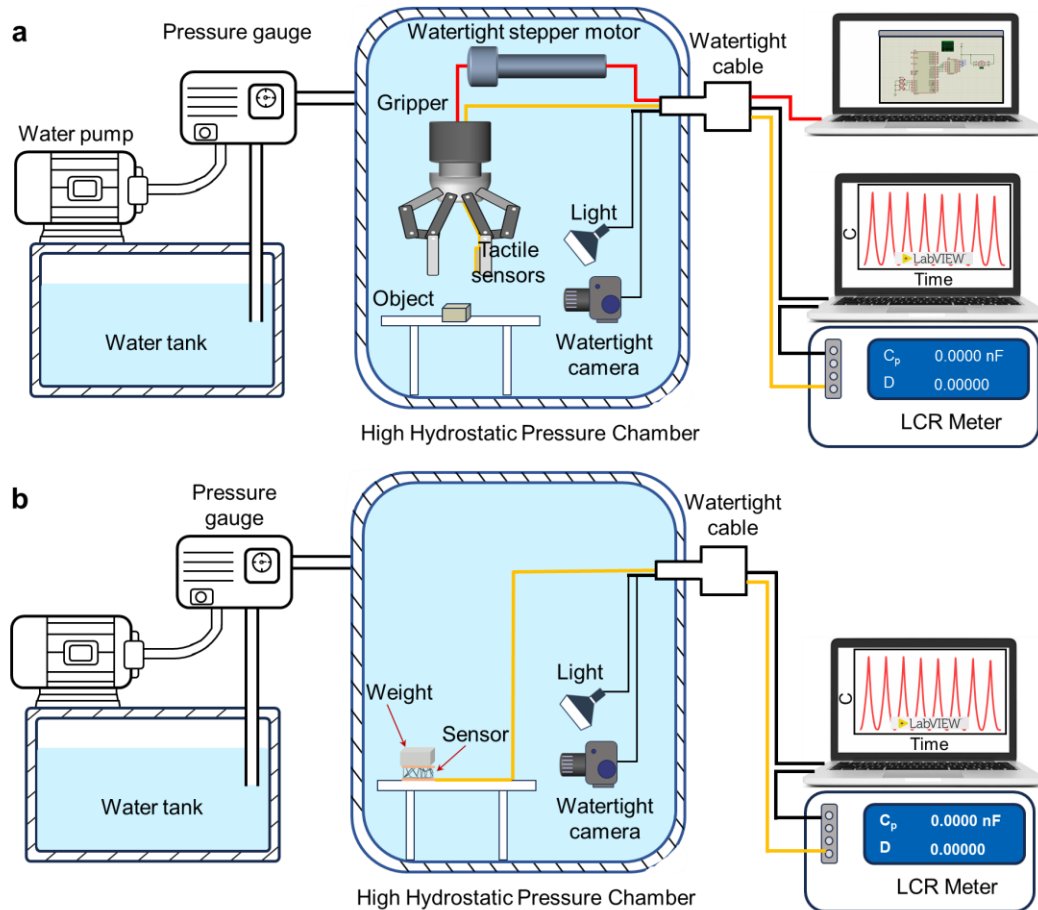


Figure S40. The schematic diagram depicts the high hydrostatic pressure environment grasping system. (a) Experimental setup for the grasping application; (b) Load application device. The pressure within the hydrostatic chamber is regulated by a water pump, while a watertight stepper motor controls the manipulator's grasping actions. Sensor responses are collected in real time through watertight cable transmission, and the entire grasping process is recorded by a camera.

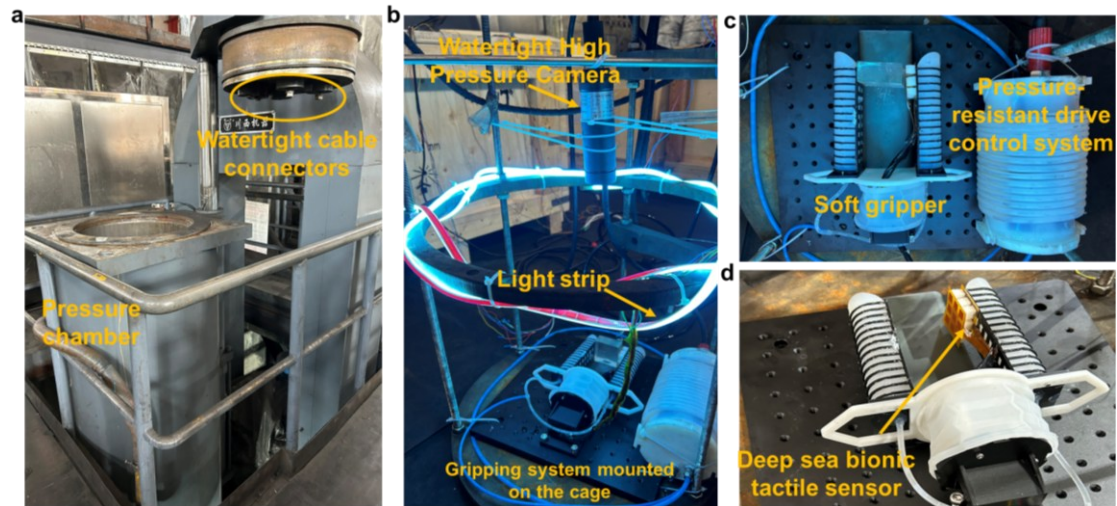


Figure S41. High hydrostatic pressure application test setup and deep sea tactile sensors arrangement. (a) High hydrostatic pressure test chamber. (b) Gripping system mounted on the cage. (c-d) The pressure-resistant soft gripper actuator and the deep-sea tactile sensor.

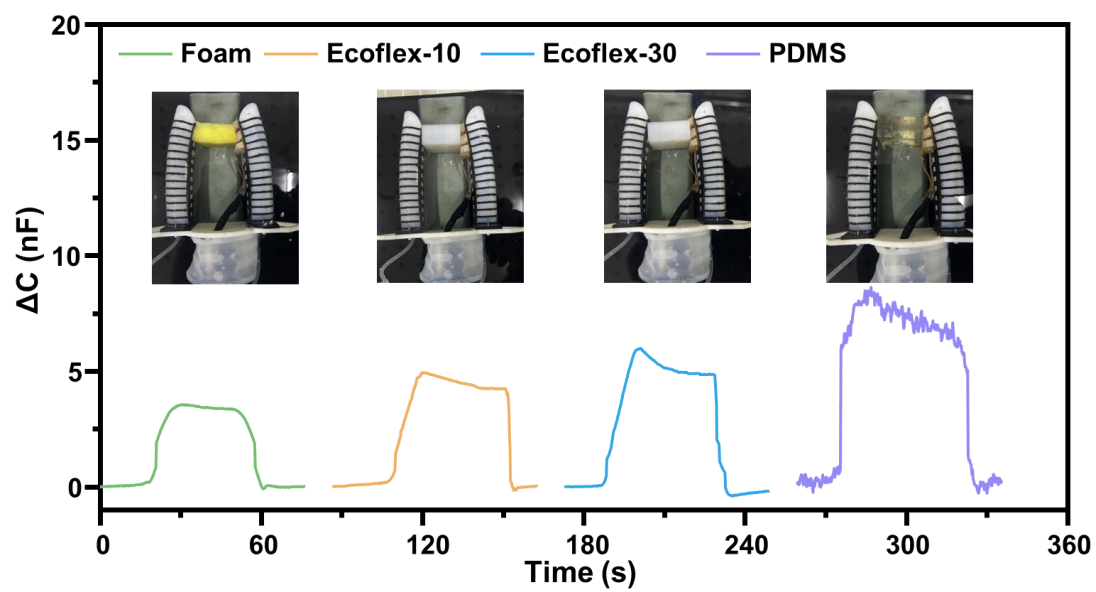


Figure S42. Grasping response of the tactile sensors at atmospheric pressure.

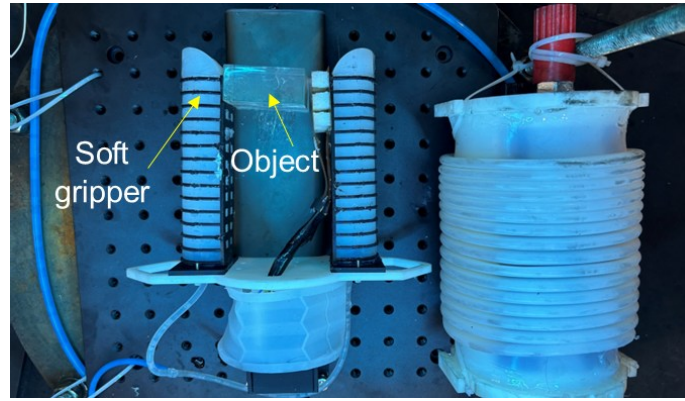


Figure S43. Experimental setup for grasping under hydrostatic pressure. The sampled object is fixed in position relative to the soft manipulator and the finger closure spacing is the same for each grasp.

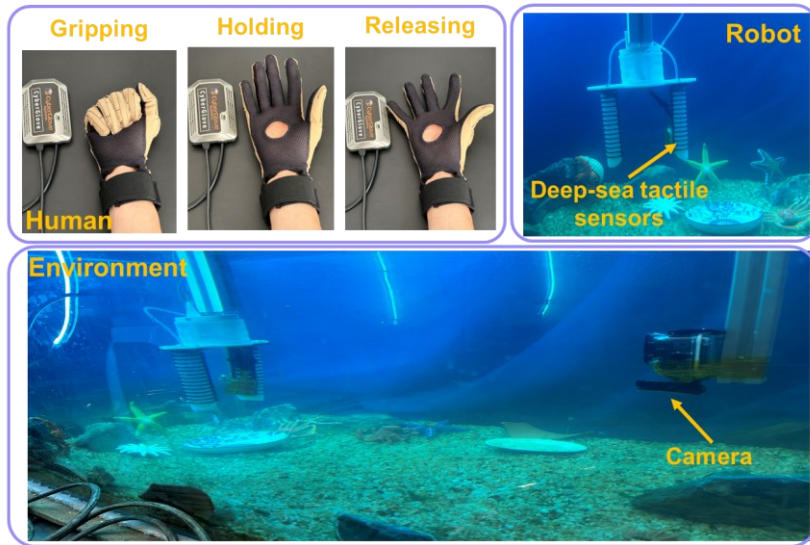


Figure S44. Experimental setup for human-robot-environment tactile feedback system.

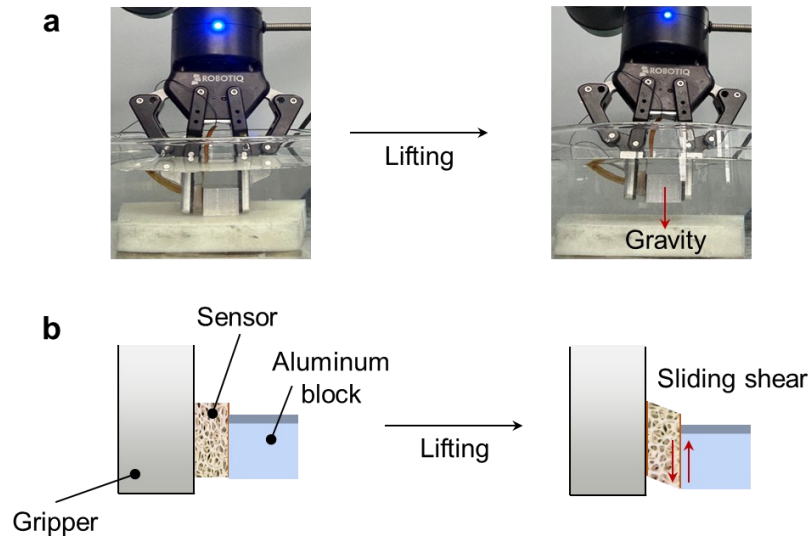


Figure S45. Schematic diagram of the aluminum block lifting process by the manipulator. (a) Schematic of the experimental process. (b) Schematic of relative sliding and capacitance variation mechanism. During the lifting process, gravity causes relative sliding between the aluminum block and the sensor surface (mounted on the manipulator fingertip). This relative sliding induces morphological changes in the sensor's sensitive layer, which further leads to fluctuations in the sensor's capacitance signal.

Table S1 The performance comparisons of underwater tactile sensors

Device	Underwater depth	Tactile sensing	Commercial rigid chips	Material Durability (Underwater)	Application	Ref.
Piezoresistive sensor	<1 m	Yes	No	10-day	Contact Force Detection	[4]
Magnetoelastic force sensor	25 m	Yes	No	21-day	Waste Sorting	[5]
Iontronic force sensor	40 m	Yes	No	10-day	Shape Mapping	[6]
Iontronic tri-axis force sensor	50 m	Yes	No	N/A	Force Detection	[7]
Piezoionic force sensor	100 m	Yes	No	N/A	Hardness differentiation	[8]
Optical waveguide force sensor	2700 m	Yes	No	N/A	Biological sampling	[9]
Magnetic SDEFS sensor	5000 m	Yes	Yes (100 \$)	N/A	Hardness testing	[10]
Deep-sea iontronic skin	5000 m	Yes	No	11-day	Object Classification/ Non-Destructive Operations	This work

Note: The “N/A” denotes no relevant performance data.

Table S2 The stability comparisons of underwater sensing functional materials

Components	Underwater stabilization time	Swelling ratio	Long-term stability (underwater)	Application	Ref.
P(DMAEMA- <i>co</i> - HEA)-SDS-C ₁₈ -Fe ³⁺	12 h	26%	72 h	Strain sensor	[11]
SF/TA@PPy	3 days	15%	9 days	Strain sensor	[12]
BA-AA-CABIL-TA	4 days	7%	15 days	Strain sensor	[13]
PVA/PSBMA-H ₂ SO ₄	5 days	6%	30 days	Strain sensor	[14]
PVA/P (SBMA- <i>co</i> - HEMA)	5 days	9%	30 days	Strain sensor	[15]
PM/M/A hydrogels	2 days	6%	20 days	Pressure sensor	[16]
P([BMIM]TFSI-<i>co</i>- BA-<i>co</i>-MMA)	3 days	4.7%	10 days	Tactile sensor	This work

Note: “Underwater stabilization time” refers to the time required for the material to reach stable performance after being immersed in water.

Table S3. Performance comparisons of underwater tactile sensors

Ref.	Underwater depth	Sensitivity	Linearity (R^2)	Linear range	Response/recover time (ms)	Stability (cycles)
[4]	<1 m	0.0338 kPa ⁻¹	/	0.06-150 kPa	100, 400	3000
[17]	<1 m	0.024 kPa ⁻¹	/	0-200 kPa	21, 23	10000
[18]	80 cm	0.195 V kPa ⁻¹	0.977	5-50 N	85, /	3500
[7]	50 m	0.058 N ⁻¹	0.999	0-12 N	200, 250	3000
[19]	100 m	1.2 kPa ⁻¹	/	45-625 kPa	150, 530	1200
[8]	100 m	0.62 kPa ⁻¹	/	50-600 kPa	190, 670	1500
[10]	5000 m	82.62 N ⁻¹	/	0-1 N	30, 30	/
This work	5000 m	0.667 kPa⁻¹	0.9977	0-10 kPa	180, 200	5000

Note: The symbol “/” in the table indicates that the corresponding performance parameter is not reported or specified in the referenced study.

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