

A dynamically tunable iontronic pressure sensor featuring a dual-dielectric-layer biomimetic structure inspired by cockroach antennae

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ABSTRACT: Under high-pressure conditions, the microstructure of flexible pressure sensors tends to become saturated, potentially leading to structural collapse and irreversible damage, which consequently results in drastically reduced sensitivity, limited pressure range, and poor repeatability. Inspired by the structural features and efficient sensing mechanisms of cockroach antennae, this study develops a biomimetic composite dual-dielectric-layer iontronic pressure sensor. The sensor integrates a self-filled microstructured upper dielectric layer, simulating the sensory array structure, the wrinkled structure of the antennae and the dynamically tunable graded contact process of the antennae, with a fabric-based lower dielectric layer infused with ionic liquid, mimicking neural fiber networks. The synergistic effect of the dual-dielectric-layer structure endows the sensor with exceptional performance, including remarkable sensitivity (1569.9 kPa^{-1}), a comprehensive pressure detection range, an ultralow detection limit, fast response and recovery times, and remarkable durability. This study provides an innovative strategy the large-scale, low-cost fabrication of sensors, showcasing significant application prospects in medical monitoring, human-machine interaction, handwriting recognition, and information encryption.

KEYWORDS: cockroach antennae, biomimetic dual-dielectric-layer, self-filled microstructure, dynamic tunability, iontronic pressure sensor

1 Introduction

Flexible pressure sensors are capable of converting external mechanical stimuli into measurable electrical signals and have been extensively applied in emerging applications such as environmental monitoring, wearable technology, and artificial intelligence [1–4]. According to different sensing mechanisms, pressure sensors can be

generally classified into four types: piezoresistive [5, 6], capacitive [7, 8], piezoelectric [9, 10], and triboelectric [11, 12]. Among them, capacitive pressure sensors have attracted extensive attention due to their advantages of simple structure, low power consumption, and high stability [13–15]. Nevertheless, traditional capacitive sensors usually suffer from low sensitivity and limited detection range under high pressure. These limitations primarily arise from the incompressibility of dielectric materials under external force, which results in insufficient variation changes in dielectric thickness and thus hinders further enhancement of sensor performance [16, 17].

In recent years, novel capacitive pressure sensors based on the electric double layers (EDL) mechanism have emerged as a research hotspot [18–22]. Departing from conventional parallel-plate capacitor designs, these sensors utilize ionic materials as the

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dielectric layer to replace traditional dielectrics, which facilitate the formation of a stable electric double layer at the electrode–dielectric interface, substantially enhancing the capacitive response [23–25]. The incorporation of ionic media in ionic capacitive pressure sensors enables the formation of nanoscale EDL at the electrode/dielectric interface, generating substantially higher interfacial capacitance than conventional capacitors. Consequently, external pressure induces ionic redistribution and conformational changes in the EDL structure, leading to a pronounced capacitive response. Furthermore, ionic materials such as ion gel offer excellent flexibility and biocompatibility, positioning them as uniquely advantageous components for advanced sensing applications. Researchers have demonstrated that constructing surface microstructures, such as micropillar arrays [26], micro-pyramids [27], and domes [28], can significantly improve device sensitivity. For instance, Cheo et al. [29] achieved a sensitivity of 41.64 kPa^{-1} using an inverted micro-pyramid structure based on ion gels, despite having a force response width of merely 0.5 kPa . This indicates that the incorporation of ion polymers markedly improves sensitivity, with output response reaching the nanofarad (nF) level, surpassing the picofarad (pF) output of conventional non-ionic flexible capacitive sensors by over three orders of magnitude. Similarly, Wu et al. [30] biomimetic the structure of beetle legs, fabricated a gradient-tilted structure via fused deposition modeling based three-dimensional (3D) printing technology. However, the complex manufacturing processes and high production costs somewhat hinder its large-scale application. Yang et al. [31] proposed a programmable microstructure fabrication strategy, utilizing CO_2 laser engraving to create gradient micropylamid structures on substrates, enabling the fabrication of capacitive pressure sensors with graded microstructures. Despite the notable advancements in sensor performance, the inherent compression modulus limitations of elastomeric materials and geometric constraints of microstructures lead to compression deformation saturation beyond a critical pressure threshold, resulting in a sharp decline in device sensitivity. Structural collapse under excessive pressure induces irreversible deformation, causing sensor failure in critical applications such as industrial gripping, healthcare monitoring, and human–machine interaction. This severely restricts their potential for high-sensitivity, wide-range, and repeatable sensing applications under high pressure. Furthermore, existing microstructures fabrication techniques typically involve complex photolithography processes or additive manufacturing methods, which are cost-prohibitive [32]. Therefore, there is an urgent need to develop a capacitive pressure sensor capable of synergistically realizing high sensitivity, a broad detection range, and robust repeatability under high-pressure conditions for viable practical applications.

Drawing inspiration from the structural features and efficient ion migration mechanism of cockroach antennae, we designed a biomimetic composite dual-dielectric-layer iontronic pressure sensor (BDLIPS) capable of delivering ultrahigh sensitivity, a broad pressure range, and excellent repeatability under high pressure. The sensor incorporates a bio-inspired dual-layer dielectric architecture: the upper layer of ion gel is constructed via a sandpaper transfer method to form a concave–convex interface with self-filling properties, simulating the sensory array structure, the wrinkled structure of the antennae and the dynamically tunable graded contact process of the antennae, thereby increasing the effective surface area and delaying structural hardening, significantly

improving sensitivity. The lower layer utilizes a fiber cloth impregnated with ionic liquid and mimicking neural fiber network to enhance structural strength and stability. The synergistic effect of the biomimetic dielectric double-layer structure endows the sensor with high sensitivity (1569.9 kPa^{-1}), a broad pressure detection range (up to 353.78 kPa), a low detection limit (2 Pa), fast response and recovery times (on the millisecond scale), and long-term durability exceeding 7500 cycles. Experimental results further demonstrate that the sensor is not only suitable for high-precision monitoring of various human physiological signals but also can be integrated with deep learning algorithms to achieve accurate recognition of different objects with an accuracy rate of 99.04%. This study provides an innovative strategy for the large-scale, low-cost fabrication of high-performance ionic capacitive pressure sensors, showcasing significant application prospects in medical monitoring, handwriting recognition, assisted communication, and in human–machine interaction.

2 Results and discussion

2.1 Inspiration and design of the BDLIPS

In nature, insects utilize antennae to perceive changes in complicated surrounding environments. Distinct from mammalian whiskers, these antennae are endowed with a diverse array of sensory receptors in microscale size, including specialized structures for detecting tactile stimuli, temperature fluctuations, and humidity levels. The cockroach antenna, a product of over a hundred million years of evolution, possesses remarkable sensitivity [33, 34]. It is capable of detecting minute pressure variations, mechanical vibrations, and air currents. As illustrated in Fig. S1 in the Electronic Supplementary Material (ESM), under the guidance of its antennae, cockroach exhibits unique characteristics, such as escape behavior, crevice detection behavior and wall-following behavior. The escape behavior refers to cockroaches avoiding the risk of contact with predators through antennal sensing, enabling them to distinguish tactile cues from natural enemies such as spiders versus those of conspecifics. Furthermore, cockroaches are capable of squeezing through extremely narrow gaps, a process in which their antennae play a critical role. The antennae are first inserted into the crevice to assess the internal structure. Based on feedback from the antennae, the cockroach adjusts its body posture to pass through the gap. The wall-following behavior indicates the positive orientation cockroaches exhibit toward walls during locomotion, showing a preference for moving along wall surfaces. During such wall-guided movement, their antennae extend forward to maintain contact with adjacent walls. The mechanosensory process in cockroach antennae involves the activation of mechanoreceptors by external stimuli, followed by signal transduction through neural pathways, which ultimately elicits adaptive behavioral responses. As illustrated in Fig. 1(a) and Figs. S2 and S3 in the ESM, the antennae of cockroach represent a highly sophisticated biological sensory organs, consisting of the scape, pedicel, and flagellum. The surface of the antennae is densely covered with various types of mechanoreceptors, forming a distinctive rough microstructure that significantly increases the specific surface area of the antennae. This structural feature significantly amplifies the antennae's sensitivity to subtle tactile stimuli and minute variations. Upon contact with objects, these mechanoreceptors respond to tactile stimuli by converting them

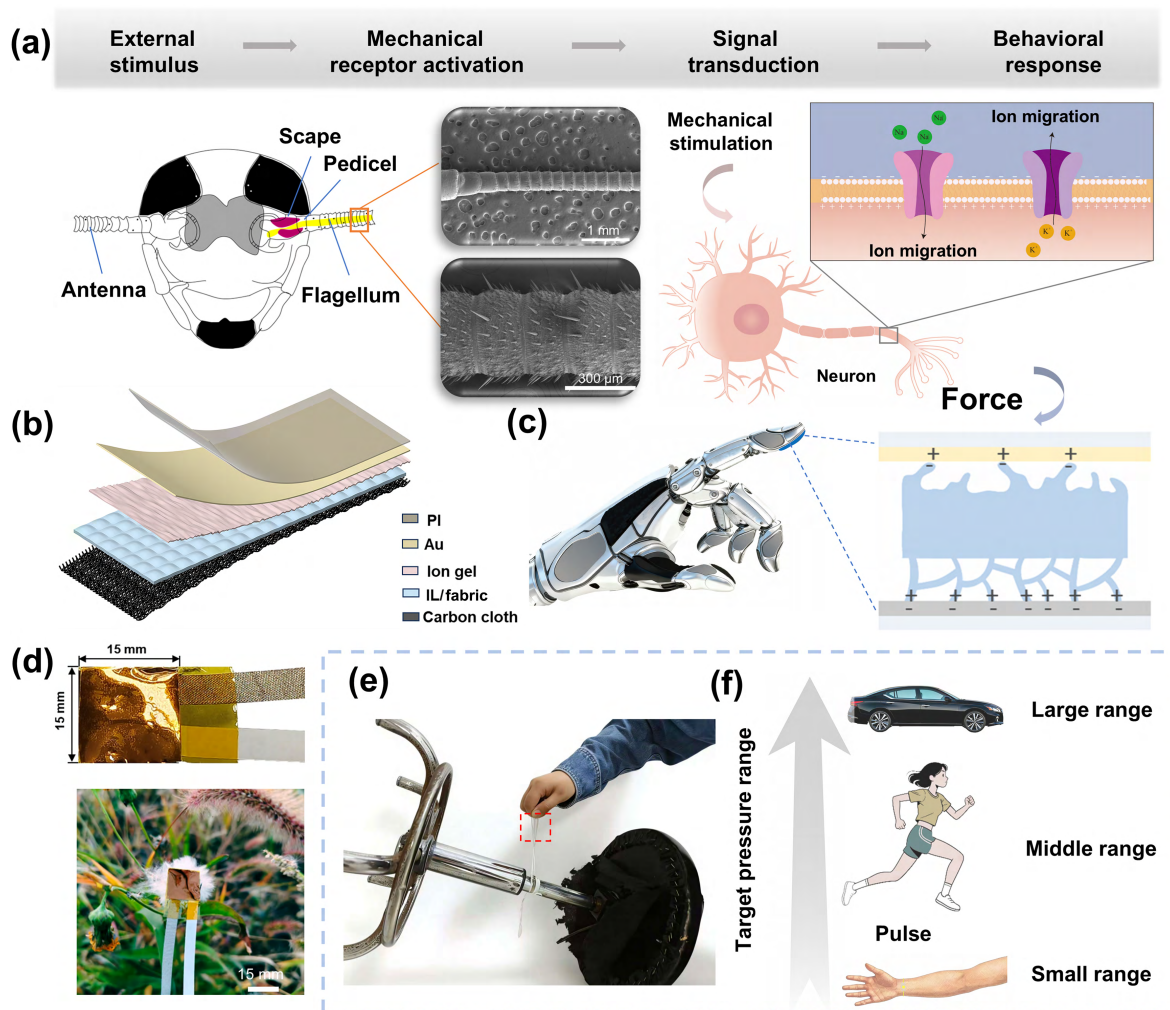


Figure 1 Schematic illustration of the design Principle for the BDLIPS. (a) Mechanical perception mechanism of cockroach antennae. (b) Schematics illustrations of the antenna-mimicking design of the BDLIPS. (c) Sensing mechanism of the BDLIPS. (d) Optical images of the BDLIPS. (e) The ion gel lifts the bench. (f) Design concept of the developed BDLIPS.

into bioelectric signals. Meanwhile, the complex network of neural fibers within the antennae, along with the efficient ion migration mechanisms, work together to respond to the stimuli, endowing the antennae with exceptional perceptive capabilities.

As shown in Fig. S4 in the ESM, the surface of cockroach antennae is densely populated with mechanoreceptors, primarily including sensilla chaetica, sensilla trichodea, and campaniform sensilla. These mechanoreceptors, which vary in height and morphological structure, work in concert to enable the detection of diverse mechanical stimuli. In addition, the antennal cuticle exhibits a wrinkled microstructure, the morphological feature that plays a significant role in facilitating efficient sensory perception. Firstly, the wrinkled structure significantly increases the effective surface area of the cuticle, providing ample topological space for the high-density distribution of sensory receptors. This ensures the rational spatial arrangement of morphologically distinct sensilla, minimizes interference among them, and supports parallel acquisition and encoding of complex environmental stimuli. Secondly, this corrugated configuration possesses favorable mechanical buffering properties. Upon contact with external objects, the folds can deform to effectively dissipate mechanical stress, thereby protecting internal structures. This mechanism safeguards the structural integrity and

functional durability of the antenna during frequent tactile interactions. Therefore, the wrinkled antennal cuticle represents an efficient spatial and mechanical optimization design. By expanding spatial capacity to optimize receptor layout and providing mechanical protection, it significantly enhances the perceptual performance of the antenna. This structure constitutes an important morphological foundation for the cockroach's adaptation to complex ecological environments.

The antennae of cockroaches achieve efficient and robust tactile perception through the ingenious coupling between their multimodal mechanosensory arrays and the folds of the cuticle. The surface of the antennae is densely populated with mechanoreceptors of diverse morphologies and dimensions, which not only form complementary sensing units in terms of physical properties, but also achieve three-dimensional integration via the topological interfaces provided by the folded structures. This results in a multi-layered, high-density cooperative sensing network, offering valuable inspiration for the design of pressure sensor. As shown in Fig. 1(b), inspired by the structural characteristics and efficient sensory mechanisms of the cockroach antennae, we have designed a biomimetic double-dielectric ionic pressure sensor. This sensor comprises two electrodes and a biomimetic double-dielectric

layer, which converts external pressure stimuli into measurable capacitive signals. The upper dielectric layer of the sensor is constructed by the sandpaper transfer method, forming a concave–convex interface with self-filled characteristic. Under high-pressure conditions, the three distinct populations of height-graded mechanoreceptors on the cockroach antenna undergo gradual compression. The wrinkled cuticular architecture furnishes additional deformation space, dissipating most of the mechanical energy via self-deformation, thus averting irreversible structural failure. The upper dielectric layer effectively emulates the multimodal sensory array structure, the wrinkled structure of the antennae and the dynamically tunable graded contact process of the antennae, thereby increasing the effective surface area, avoiding structural hardening under high-pressure loading, and significantly improving the sensitivity. The lower dielectric layer adopts fiber cloth impregnated with ionic liquid to simulate the neural fiber network, enhancing the structural strength and stability. When the circuit is activated, anions and cations within the dielectric layer migrate toward their respective electrodes, forming an EDL that underpins the high sensitivity and signal stability of the device (Fig. 1(c)).

Figure 1(d) shows the optical image of the biomimetic composite BDLIPS. The lightweight and soft nature of BDLIPS allows it to be readily placed on *Cichorium intybus* pappus, when used for monitoring physiological, it avoids the discomfort caused by the sensor pressing on the body enabling long-term wearability. As shown in Fig. 1(e) and Fig. S5 in the ESM, the ionic gel film demonstrates remarkable load-bearing capability, capable of suspending a weight about 2.2 kg. This result underscores its exceptional mechanical robustness, which is critical for ensuring stable sensor operation under high mechanical load. As illustrated in Fig. 1(f), our positive design strategy for scenario-specific pressure sensors.

2.2 Fabrication process and working principle of the BDLIPS

Figure 2(a) illustrates the fabrication process of the biomimetic self-filled microstructure forming the upper dielectric layer.

Initially, a mixed solution of polyvinyl alcohol (PVA)/ H_3PO_4 was cast onto the surface of sandpaper. After the solution fully infiltrated the rough surface of the sandpaper, it was dried at room temperature and subsequently peeled off, yielding an ionic gel film with well-defined microstructures (details can be found in the Experimental section). During the preparation of the PVA/ H_3PO_4 system, a crosslinked elastic framework was constructed through esterification, and the system exhibited the ability to dissociate a lot of mobile ions, thereby forming a film with both elasticity and ionic conductivity. Here, the incorporation of H_3PO_4 promotes the formation of an extensive hydrogen bonding network within the PVA matrix, significantly enhancing the mechanical strength and toughness of the gel. Additionally, the dissociated ionic species (H^+ , H_2PO_4^- , and HPO_4^{2-}) facilitate ion migration within the gel, providing the necessary conditions for the formation of an electric double layer. Figure 2(a) shows the preparation route of the biomimetic ionic composite fiber structure that serves as the lower dielectric layer (details in the Experimental section). All device components were fabricated from cost-effective and easily processable materials, with the microscale architectures faithfully replicated through a straightforward template-transfer strategy.

Scanning electron microscopy (SEM) characterization of the

PVA/ H_3PO_4 films replicated from the sandpaper template revealed distinct protrusions and grooves, with minimum feature sizes down to several tens of micrometers (Fig. 2(b) and Fig. S6 in the ESM). The prepared structure is analogous to the antennae of a cockroach.

In addition, the existence of ionic liquid (IL) on composite fibers is proven by energy-dispersive X-ray spectroscopy (EDS) results. As [BMIM][BF₄] in the IL is the sole source of fluorine (F) and boron (B) elements in our materials, the EDS mapping images of the F, B, C, N, and O clearly demonstrates that the IL is uniformly distributed on the fabric (Fig. 2(b) and Fig. S7 in the ESM). These experimental results clearly indicate that the IL is relatively stable in the IL/fabric composite. In addition to the above characterization experiments, Fourier transform infrared spectroscopy (FTIR) spectral analysis was conducted. Figure S8 in the ESM displays the infrared spectra of the fabric before and after IL treatment. The spectrum of untreated fabric displayed obvious absorption peaks at 3326.25, 2892.37, and 1017.06 cm^{-1} respectively, which are attributed to the O–H stretching vibrations, aliphatic C–H stretching vibrations, and C–O stretching. After being treated with IL, new characteristic peaks appeared at 3164.75 and 1573.87 cm^{-1} , corresponding to C–H stretching vibrations and C=C stretching vibrations in the imidazole ring of the [BMIM][BF₄] cation. This further indicates that the IL has been successfully transferred into the fabric. Obviously, the absorption peaks of O–H and C–H were observed to shift after being treated with IL, suggesting the possibility of interactions such as hydrogen bonding between the IL and fabric.

As shown in Fig. 2(c), to elucidate the underlying mechanism through which the microstructure of the biomimetic composite dual-dielectric-layer produces high sensitivity under high pressure, we investigated the deformability of different microstructures by performing finite element analysis (FEA). Research indicates that hemisphere microstructures exhibit significant resistance to external pressure, thereby exhibiting a poor structural compressibility. In contrast, the self-filled structure consists of protrusions and grooves at varying heights. These protrusions minimize the initial contact area between the electrode and the dielectric layer before pressure is applied. This results in an extremely low initial capacitance (C_0) on a pF scale. The pressure sensor emulates the dynamically tunable, graded contact process of antennae. Upon the application of pressure, these protrusions exhibit a tendency to bend. As the pressure increases, the higher protrusions undergo deformation, after which the electrode begins to make contact with the shorter protrusions, resulting in a gradually increasing contact area over a broad pressure range. In addition, the grooves can provide necessary space to accommodate the buckled protrusions, reducing resistance to pressure and enabling larger deformations before they full bottom contact is achieved, thereby increasing the compressibility of the structure. The biomimetic dual dielectric-layered bottom IL/fabric composite fiber network provides mechanical support, enhancing the structural compressibility of the dielectric layer. This broadens the pressure sensing range and effectively imparts strength and stability to resist deformation brought about by external pressure. These results ultimately validate the effectiveness of the biomimetic dual dielectric-layer structure strategy in optimizing the performance of pressure sensors.

Figure 2(d) illustrates the mechanism of pressure sensing of the biomimetic sensor. The composite dual-dielectric-layer is sandwiched between the gold electrode and the carbon cloth electrode. Under high pressure, the protrusions on the surface of

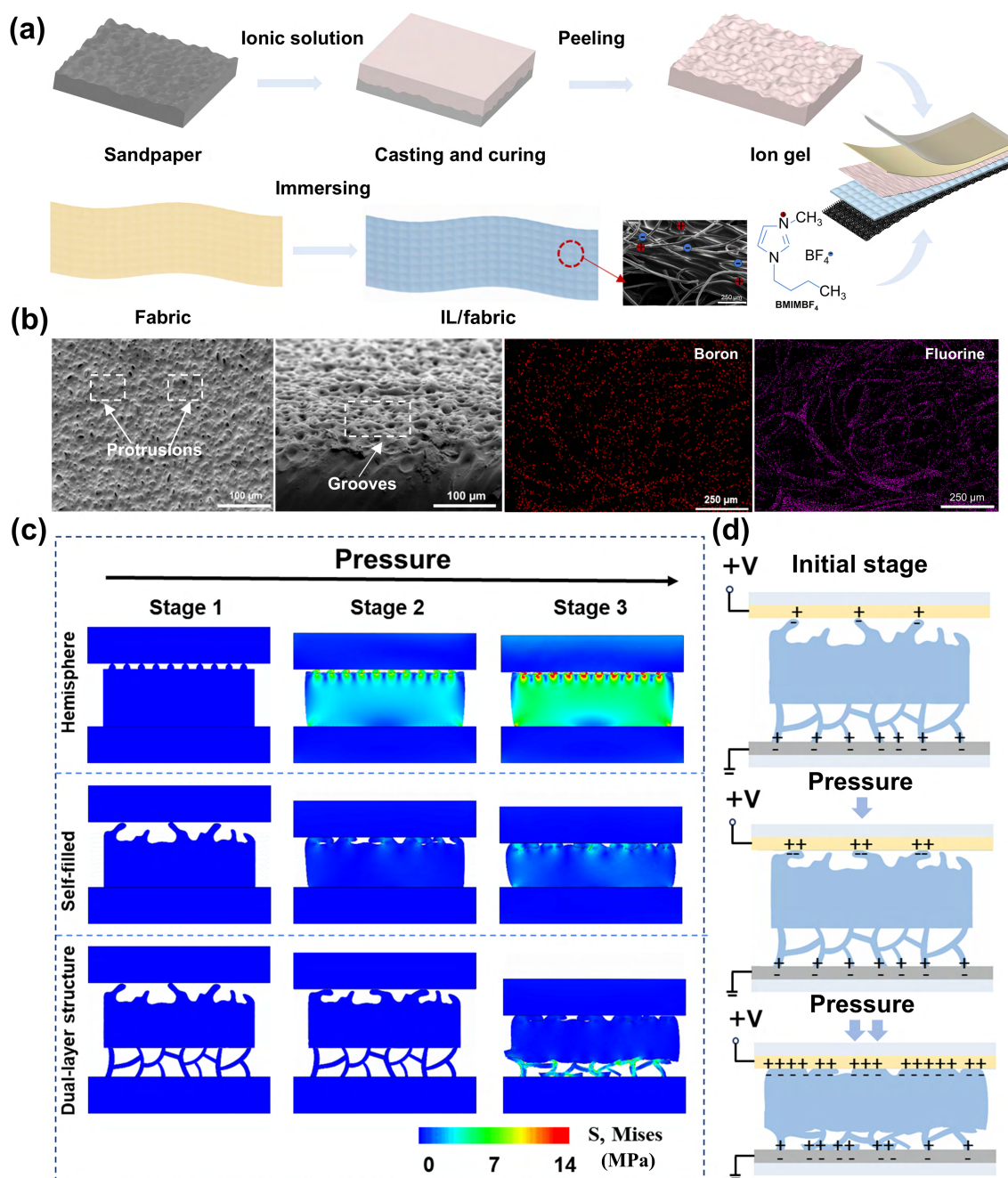


Figure 2 From design to mechanism: integrated fabrication, characterization, and simulation analysis of a the BDLIPS. (a) Schematics of fabrication process of ion gel dielectric layer and IL/fabric dielectric layer. (b) SEM images of PVA/H₃PO₄ film and EDS mapping images of the IL/fabric. (c) Simulation of stress distribution results for different architectures: a hemisphere, a self-filled, and the dual-layer structure. (d) Schematic illustration for sensing mechanism of the BDLIPS before and after applying pressure.

the PVA/H₃PO₄ film are buckled and filled into the grooves, resulting in a progressive increase of the contact area between the electrodes and the dielectric-layer. This process facilitates the creation of additional space within the dielectric layer to accommodate more counter ions, promoting the accumulation of a greater number of ion–electron pairs at the interface, which significantly enhances the rate of capacitance change. As the pressure further increases, the lower dielectric layer IL/fabric also undergoes deformation until the pressure reaches saturation. In summary, the sustained capacitance response under high pressure, arising from the coupled effects of interfacial electric double layer

modulation, dynamic ion migration, and multiscale structural deformation, which collectively endow the device with both high sensitivity and a wide sensing range.

Figure S9 in the ESM illustrates the simplified equivalent circuit model of the biomimetic sensor. There are two EDL capacitors formed at the interface between the upper electrode (denoted as C_{EDL1}) and the upper dielectric layer and the lower dielectric layer and the lower electrode (denoted as C_{EDL2}), respectively. The two capacitors are connected in series with a bulk resistance (R) and are coupled in parallel with a capacitance C_p , which is generated by the two electrodes. The measured capacitance can be defined as

$$C = 1/(1/C_{EDL1} + 1/C_{EDL2}) + C_p \quad (1)$$

The capacitance of C_{EDL1} and C_{EDL2} is highly changed upon loading, whereas the capacitances of C_p is considerably smaller in comparison to that of the EDL, such that it can be neglected.

2.3 Sensing performance of the BDLIPS

Sensitivity is one of the key parameters for evaluating the performance of pressure sensors. In this study, the regulatory mechanism of microstructural morphology on sensor sensitivity was systematically analyzed. Different grit sandpapers (280#, 600#, 1000#, and 2000#) were used to transfer microstructures onto the surface of the bionic dielectric layer's upper ion gel film. As shown in Fig. 3(a), the sensitivity of the sensor exhibits an initial increase followed by a decrease as the grit number increases. Figure S10 in the ESM indicates that the microstructural dimensions and density of the ion gel film surface significantly differ depending on the grit number: sandpapers with lower grits (e.g., 280#) form larger structures (approximately tens of micrometers) with fewer structures per unit area, whereas higher grits result in smaller microstructures (for instance, structures prepared with 1000#

sandpaper are approximately 15 μm) and a notably higher structural density. The sensitivity (S) can be defined as the ratio of the relative capacitance change to the applied pressure

$$S = (\Delta C/C_0)/\Delta P \quad (2)$$

where ΔC ($\Delta C = C - C_0$) represents the change in capacitance, C_0 is the initial capacitance, C is the measured capacitance, and ΔP is the change in pressure.

The compression characteristics curve shown in Fig. S11 in the ESM further demonstrates that the film transferred using 1000# sandpaper exhibits the most optimal mechanical behavior during compression. This is because the medium-sized microstructures can achieve more efficient force transfer and a larger deformable space per unit area. However, when the sandpaper grit exceeds 1000#, the microstructure size becomes too small, limiting the deformation capability of individual structures, which leads to a decline in overall compression performance and, consequently, a reduction in sensitivity. Based on this analysis, 1000 grit sandpaper was selected for the preparation of ion gel films in this study to achieve high sensitivity and good compression performance (Fig. S12 in the ESM). The sandpaper transfer method has good

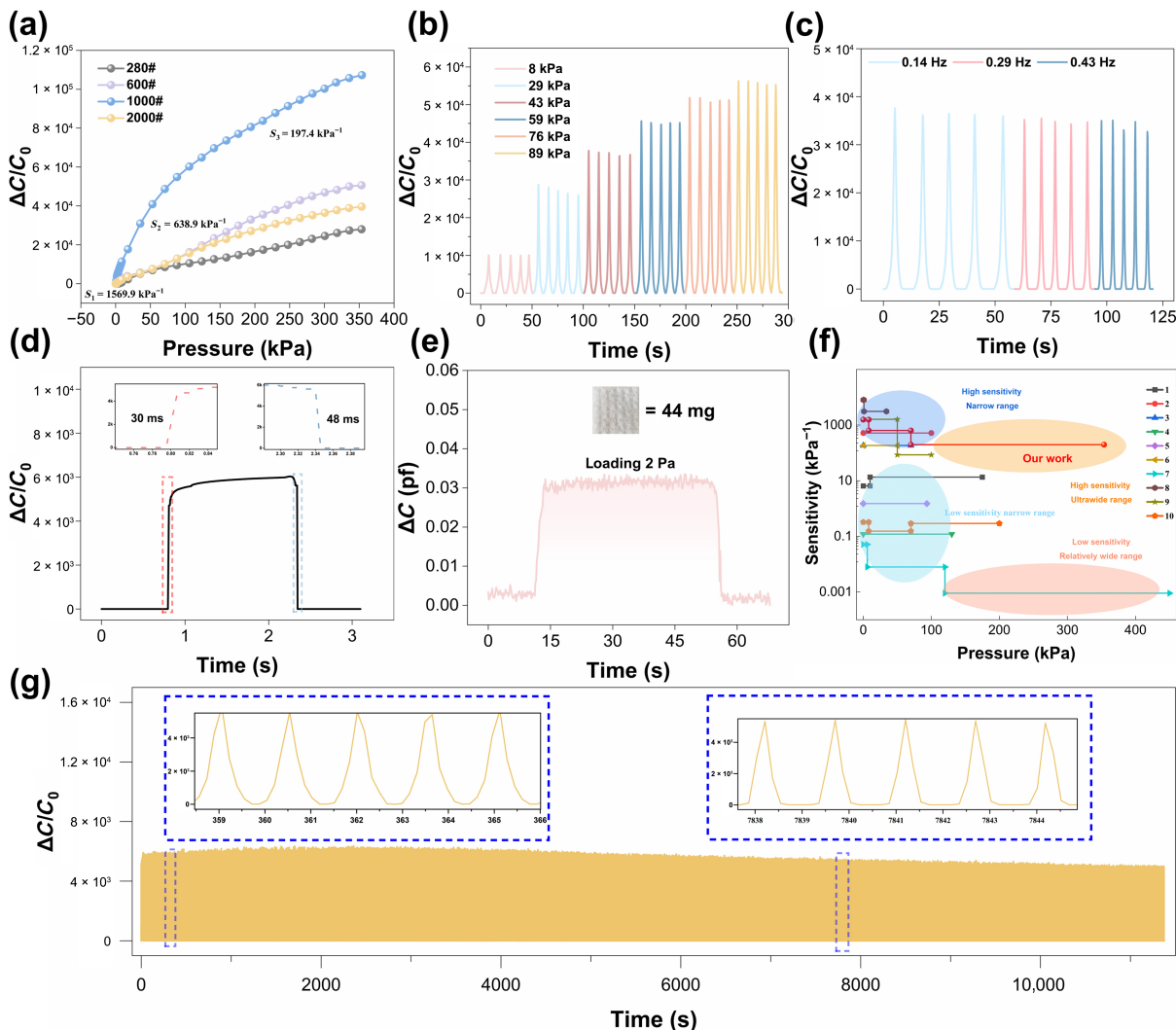


Figure 3 Sensing performance of the biomimetic sensor. (a) Sensitivity of the biomimetic sensor at pressure range up to 353.78 kPa. (b) Dynamic response curves of the biomimetic sensor under different pressures. (c) Response of our sensor at different compression frequencies. (d) Response and recovery time of the sensor. (e) LOD of the biomimetic sensor. (f) Sensing Performance comparison of our BDLIPS with existing capacitive sensors. (g) Stability of the sensor exceeding 7500 cycles.

repeatability and consistency between batches (Figs. S13–S15 in the ESM). Figure S16 in the ESM shows the schematic diagram of the sensor performance testing device.

Experimental measurements indicate that the sensor's sensitivity in the low pressure range (< 8 kPa) is $S_1 = 1569.9$ kPa $^{-1}$, in the moderate pressure range (8–70 kPa) the sensitivity reaches $S_2 = 638.9$ kPa $^{-1}$, and in the higher pressure range (70–353.78 kPa), it still maintains a sensitivity level of above 197.4 kPa $^{-1}$. The existence of the dual-dielectric layer makes the initial capacitance of the sensor only a dozen pF. As the pressure increases, the microstructure undergoes deformation, leading to an increase in the contact area between the electrode and the dielectric layers. This results in the formation of an effective EDL, which causes in a continuous increase in the capacitance. In contrast, within the same pressure range, single-layer sensor exhibits smaller capacitance variation, lower compressibility and poorer sensing performance. As shown in Figs. S17 and S18 in the ESM, the sensor with a single-dielectric-layer self-filled ionic gel film has a sensitivity in the pressure range (< 8 kPa) is $S_1 = 725.81$ kPa $^{-1}$, in the moderate pressure range (8–225 kPa) the sensitivity reaches $S_2 = 160.71$ kPa $^{-1}$, and in the higher pressure range (225–262.08 kPa), it is only 15.01 kPa $^{-1}$. The sensor with a single-dielectric-layer made of fabric impregnated with IL demonstrates a sensitivity of only 0.72 kPa $^{-1}$. Compared to single dielectric layer-based pressure sensors, those incorporating biomimetic dual dielectric-layered structure demonstrate superior performance.

As shown in Fig. 3(b), the sensor exhibits stable capacitance responses during the different pressure cycles, with the capacitance rapidly recovering to its initial value upon decompression. Furthermore, as shown in Fig. 3(c), the sensor is capable of responding to pressure stimuli at various frequencies. Additionally, applying about 3.6 kPa-level pressure to the sensor yields response and recovery times of 30 and 48 ms, respectively (Fig. 3(d)), which are shorter than the response time of human skin. The sensor's detection limit (LOD) was validated by applying a cotton cloth with a mass of 44 mg (producing a pressure of about 2 Pa), and the results show that the sensor can detect such weak signals (Fig. 3(e)). We fabricated the BDLIPS and loaded it by placing it under a hollow iron block, a beaker containing 400 g of weights, a bottle of water, and a small solid iron block, along with 100 and 20 g weights. Enabled by the high-pressure resolution, the pressure sensor can detect the gentle placement of the 20 g weight. Each subtle pressure change can be precisely recorded by the BDLIPS (Fig. S19 in the ESM). As shown in Fig. 3(f), the performance of our sensor is also compared with other capacitive sensors recently reported [1, 30, 35–41]. Our sensor has excellent sensitivity and a wide pressure range. Mechanical durability tests demonstrate that after 7500 compression cycles under pressure, the sensor still maintains stable responsiveness (Fig. 3(g)), indicating its good cyclic lifespan and reliable dynamic performance.

2.4 Applications in wearable electronics for real-time on-body sensing and monitoring

Benefiting from its outstanding sensing performance, the proposed biomimetic pressure sensor exhibits broad application prospects in the precise monitoring of human physiological signals and dynamic motion states, thereby offering considerable promise for advancing healthcare diagnostics and real-time motion analysis [42]. As illustrated in Fig. 4(a), when the sensor is fixed at the radial artery of a volunteer, real-time acquisition of pulse signals can be readily achieved. By extracting and analyzing the corresponding output

waveform, the pulse frequency is calculated to be approximately 75 beats per minute. In the enlarged waveform, characteristic components such as the percussion wave (P) and dicrotic wave (D) can be clearly distinguished. Since pulse is a vital physiological parameter closely associated with cardiovascular health, the capability of the sensor to sensitively detect weak arterial pulsations provides a solid technical foundation for early diagnosis of cardiovascular diseases.

In addition to vital signal monitoring, the sensor also demonstrates excellent capability in motion state detection. As shown in Fig. 4(b), when adhered to the finger joint, the amplitude of the output signal increases proportionally with the bending angle, thereby enabling real-time monitoring and quantitative recognition of finger flexion movements. Furthermore, by attaching the sensor to the inner and outer sides of the wrist and elbow joints (Figs. 4(c)–4(e)), dynamic response signals of joint motions can be continuously captured, verifying its reliability in complex biomechanical scenarios.

The sensor also exhibits remarkable potential in gait recognition and locomotion analysis. As shown in Fig. 4(f), when placed on the sole, it can effectively discriminate between distinct movement patterns such as walking and running. Moreover, the device can precisely capture the dynamic variations associated with muscle contraction and relaxation (Fig. S20 in the ESM), which further expands its application scope in smart wearable devices, sports science, and rehabilitation monitoring. Notably, the sensor maintains excellent signal responsiveness, sensitivity, and repeatability across multiple physiological and kinematic contexts, underscoring its potential in next-generation healthcare monitoring, prosthetic control, and intelligent robotics.

Beyond physiological and motion detection, the sensor also demonstrates utility in human-machine interaction. As shown in Fig. S21 in the ESM, when integrated onto the surface of a mouse, it can effectively distinguish unimodal and bimodal signal responses corresponding to single and double-click operations. Furthermore, when attached to the fingertip for tactile sensing (Fig. 4(g)), the sensor reliably recognizes and outputs distinct signal patterns corresponding to light touch, medium pressure, and heavy pressure inputs, confirming its feasibility in flexible electronics, electronic-skin systems, and intelligent interactive interfaces. Remarkably, the distinctive performance of the BDLIPS enables reliable, repeated sensing of the load weight imposed by a 1.4-ton passenger vehicle (Fig. 4(h)).

As shown in Fig. S22 in the ESM, the biomimetic sensor is fixed on the outer wall of the beaker to detect the capacitance changes during the hand grasping and releasing processes. As the mass of the liquid in the beaker increases, the capacitance of the sensor exhibits a corresponding upward trend. Notably, during the repeated grasping and releasing processes, the relative capacitance change maintained a fairly high stability, further verifying the stability of the sensor in practical applications. As shown in Fig. S23 in the ESM, when the tweezers equipped with sensor are used to pick up weights of different masses, the sensor can generate different signal responses, indicating that the sensors can effectively identify the changes in force caused by different masses.

2.5 Versatile signal recognition and intelligent perception enabled by the BDLIPS

The proposed BDLIPS pressure sensor demonstrates significant potential beyond the monitoring of human physiological signals

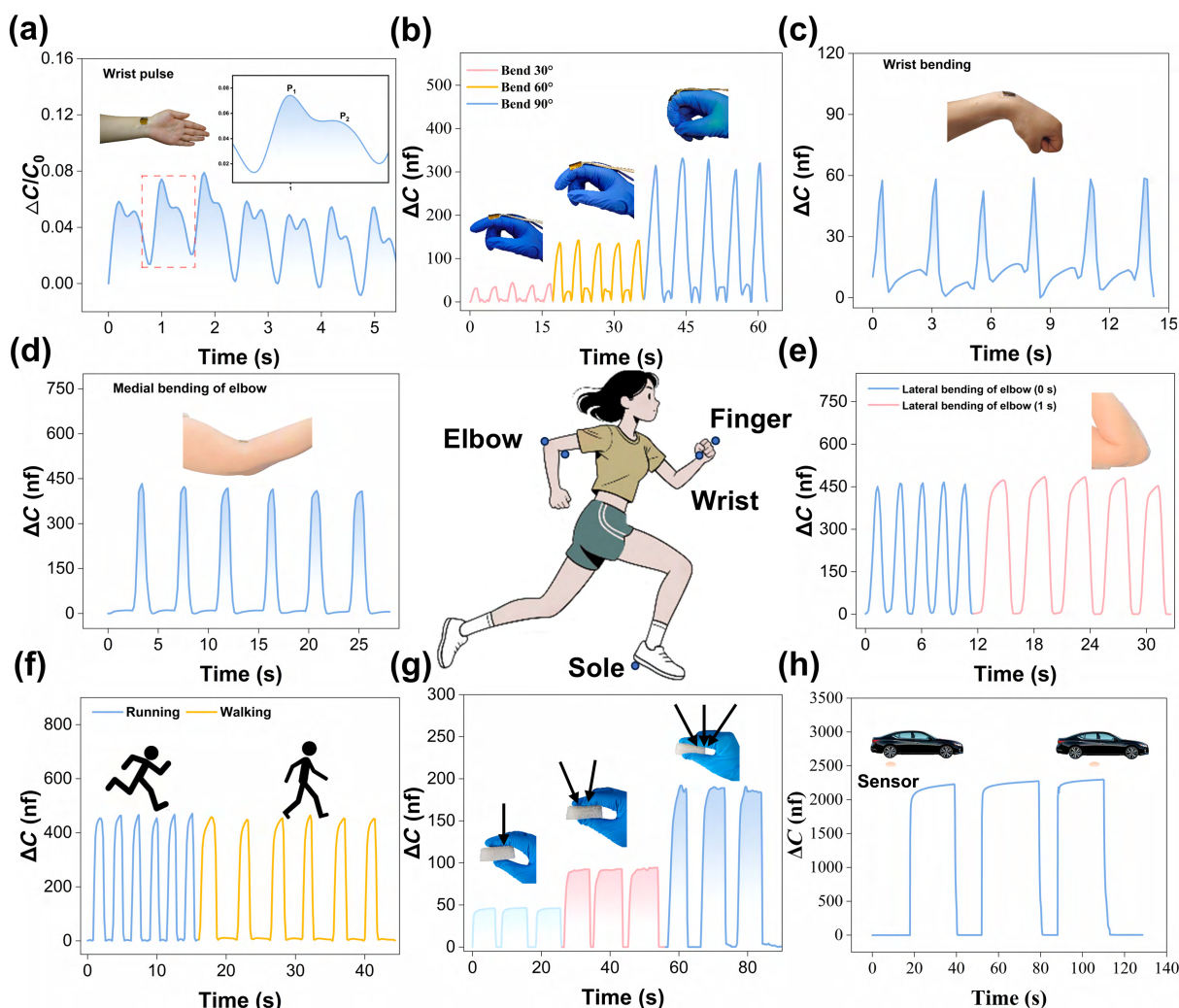


Figure 4 Applications in wearable electronics. (a) Detection of pulse signals. (b) Detection of finger bending. (c) Detection of wrist bending. (d) and (e) Detection of elbow bending. (f) Detection of running, walking motion. (g) Detection of compression states in soft matter. (h) Capacitance response of a 1.4-ton car before and after loading.

and movement states, extending to advanced human-machine interaction and communication scenarios. For instance, the sensor can be leveraged for information encoding and transmission based on Morse code principles. As illustrated in Figs. 5(a) and 5(b), the BDLIPS can be attached to fingers for communication via Morse codes. The schematic diagram presents Morse code for 26 letters. Given the instant response of the BDLIPS to finger touching, both “dots” and “dashes” are represented by the change of capacitive signals caused by brief and prolonged taps on the sensor. As shown in Fig. 5(c) and Fig. S24 in the ESM, the words of “HELP” and “SOS” can be effectively transmitted via rhythmically patterned finger taps on the sensor, highlighting its capability for intuitive and reliable coded communication. In addition, the excellent performance of the sensor makes it well-suited for integration into handwriting recognition systems [43]. As shown in Figs. 5(d)–5(f), distinct capacitive signal patterns are generated as a user writes different letters and numbers on the sensor’s surface, a result of variations in stroke sequence and pressure distribution.

Furthermore, as shown in Fig. 5(g) the BDLIPS sensor shows great potential for robotic manipulation applications by providing precise sensing and feedback. Figure S25 in the ESM shows the

AM1 intelligent robotic arm. As shown in Fig. 5(h), we integrate the sensor into a robotic gripper. When the gripper grasps different objects, the capacitive pressure sensors exhibit distinct signal responses. We adopt deep learning technology to analyze the signals captured by the sensor. Figure S26 in the ESM shows 7 objects of diverse materials and shapes selected to build the training dataset, with each object being grasped 100 times using the mechanical gripper. As shown in Fig. 5(i), it is the program diagram of the testing device, including a computer, a controller, a mechanical gripper, a BDLIPS and an inductance-capacitance-resistance (LCR) meter.

The BDLIPS installed on the inner side of the robotic gripper generated fully different signal waveforms by grasping different objects (Fig. 5(j)). The signal waveforms were highly reproducible by repeatedly grasping the objects, suggesting the reliability of tactile sensation using the BDLIPS. Figure 5(k) illustrates the sensing signals corresponding to the grasping of 7 objects, with a total of 700 capacitance “ΔC” data samples collected. The acquired data is randomly divided into training set (70%) and test set (30%). We established a sensor signal classification system based on one-dimensional convolutional neural network (1D-CNN), and verified

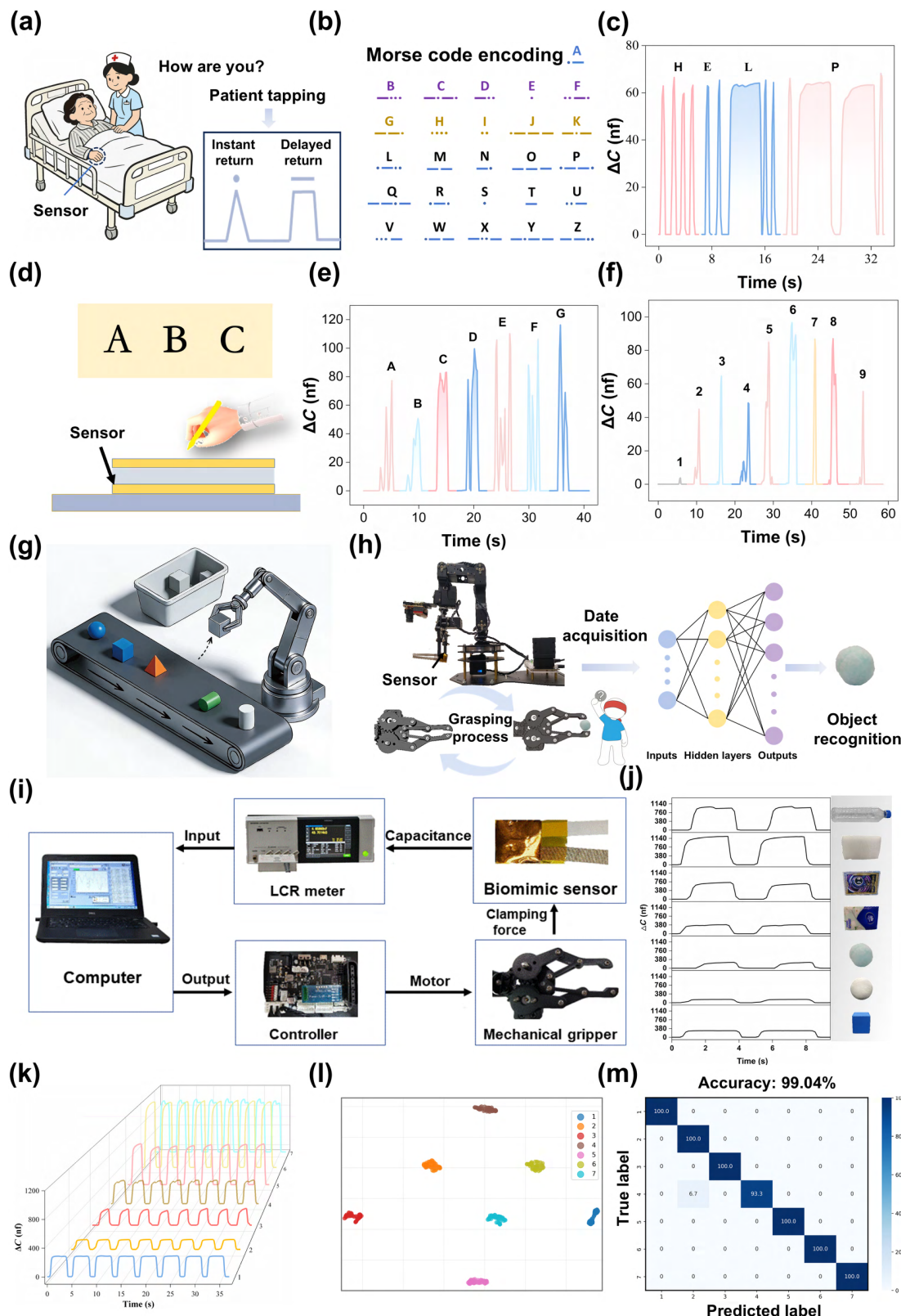


Figure 5 Application of BDLIPS in wearable human-machine interfaces. (a) Schematic diagram of potential application scenarios for the BDLIPS based Morse code translation system. (b) Schematic illustration of Morse code for 26 letters. (c) “HELP” by tapping the sensor with finger according to Morse code. (d) Schematic diagram of handwriting recognition. (e) Responses of the BDLIPS when handwriting the letters on it. (f) Responses of the BDLIPS when handwriting the Arabic numerals on it. (g) Schematic diagram of potential application scenarios for the BDLIPS installed on the robotic hand. (h) Schematic illustration of the mechanical gripper equipped with BDLIPS. (i) Schematic of the closed-loop control system, including a computer, a controller, a mechanical gripper, a BDLIPS and an LCR meter. (j) Typical output signals of BDLIPS installed on the robotic hand grasping 7 different objects. (k) Output signals by repeatedly grasping the objects. (l) Visualization results corresponding to the classification of 7 object signals. (m) Confusion matrix for the mechanical gripper grasping 7 objects, with a recognition accuracy of 99.04%.

the feature learning ability of the deep learning model through dimensionality reduction visualization technology. The constructed CNN model includes three convolutional layers. Each layer is equipped with batch normalization and ReLU activation functions. Max pooling and adaptive average pooling are employed for feature dimensionality reduction. Finally, the classification of seven categories of sensor signals is achieved through the fully connected layer. During the training of the model, we chose Adam optimizer. The learning rate was set to 0.001.

To verify the feature learning effect of CNN, the study further adopted the t-distributed Stochastic Neighbor Embedding (t-SNE) dimensionality reduction technique to perform a comparative analysis of the original standardized data and the features extracted by the CNN through two-dimensional visualization. As shown in the Fig. 5(l), it is the visualization results of the BDLIPS pressure sensor signal database. The experimental results demonstrate that, compared with the original signal data, the high-level features learned by the CNN exhibit better class separability in the t-SNE projection space. Quantitatively evaluated by the Silhouette Coefficient, the inter-class separation degree of CNN features is significantly better than that of the original features, validating the effectiveness of deep learning models in feature extraction and pattern recognition of the sensor signals. As shown in Fig. 5(m), the trained deep learning model achieved a recognition accuracy of 99.04% on the test set. This sensor demonstrates significant potential for application in fields such as intelligent manufacturing and human-machine interaction.

3 Conclusions

In this study, inspired by the structural features and efficient sensing mechanisms of cockroach antennae, a biomimetic composite BDLIPS was successfully fabricated. The upper dielectric layer, designed via a sandpaper transfer method, increasing the effective surface area and avoiding structural hardening under high-pressure loading, significantly improving sensitivity. The lower layer, made of fabric impregnated with IL, mimics neural fiber networks to boost structural strength and stability. The combined biomimetic design endowed the sensor with exceptional sensitivity (1569.9 kPa^{-1}), a broad pressure detection range up to 353.78 kPa , low detection limit, fast response and recovery times of 30 and 48 ms, and remarkable durability exceeding 7500 cycles. Notably, even under high-pressure conditions ($70\text{--}353.78 \text{ kPa}$), it still maintains an outstanding sensitivity level of 197.4 kPa^{-1} . Experimental results further demonstrate that the sensor is not only suitable for high-precision monitoring of various human physiological signals but also can be integrated with deep learning algorithms to achieve accurate recognition of different objects with an accuracy rate of 99.04%, showcasing the potential in intelligent logistics sorting. This innovative approach offers a promising pathway for low-cost, large-scale production of high-performance pressure sensors, with potential applications in medical monitoring, human-machine interaction, handwriting recognition, and assisted communication.

4 Experimental section

4.1 Materials

The PVA was purchased from Aladdin Industrial Corporation. The H_3PO_4 was purchased from Shanghai Macklin Biochemical Co., Ltd. The sandpaper used was German Warrior brand sandpaper.

The $[\text{BMIM}][\text{BF}_4]$ was purchased from Shanghai Macklin Biochemical Co. The polyimide (PI)/Au film was purchased from Tian Hou New Materials.

4.2 Fabrication of PVA/ H_3PO_4 ionic films as the top layer of the dielectric

Commercial sandpaper (1000#) was used as the template for preparing ionic films. First, 3 g of PVA ($M_w \sim 145,000$, from Aladdin Industrial Corporation) was dissolved in 27 g of deionized water, heated and stirred at 90°C for 2 h until the PVA was fully dissolved. After cooling the mixed solution to room temperature, an appropriate amount of H_3PO_4 (from Shanghai Macklin Biochemical Co., Ltd.) was added to the PVA solution, followed by stirring for 2 h to ensure homogeneous mixing. The resulting PVA/ H_3PO_4 solution was poured onto a commercial sandpaper template and subjected to curing at 30°C for 24 h. Finally, ionic film of PVA/ H_3PO_4 was carefully peeled off for later use.

4.3 Fabrication of ion composite fiber as the lower layer of the dielectric

The fiber fabric was subjected to ultrasonic treatment in ethanol for 30 min to remove impurities and dirt on the surface. After pretreatment, the fabric was dried in an oven at 50°C for 2 h. Subsequently, the dried fabric was immersed in IL ($[\text{BMIM}][\text{BF}_4]$, purity $\geq 98\%$) solution for 10 min to prepare the lower layer of the dielectric. After immersion, the fabric was gently removed using tweezers, and excess ionic liquid within the fabric's pores was squeezed out to ensure uniform distribution of the solution throughout the fiber structure. Finally, the sample was placed on absorbent paper to absorb any residual ionic liquid remaining on the surface.

4.4 Assembly of pressure sensor

The PI/Au film, PVA/ H_3PO_4 ionic gel film, composite ionic fiber layer and conductive carbon cloth were precisely fabricated into $15 \text{ mm} \times 15 \text{ mm}$ sizes through laser cutting, serving as the upper electrode layer, upper dielectric layer, lower dielectric layer and lower electrode layer of the pressure sensor. Then, the upper electrode layer, bionic double-layer dielectric structure and lower electrode layer were stacked from top to bottom. The layers were bonded together using 3M double-sided adhesive tape to ensure structural integrity. Finally, the assembled pressure sensor was encapsulated in PI film for protection and enhanced durability.

4.5 Finite element analysis (FEA)

The FEA was conducted using the commercial package ABAQUS 2024. The electrode layer was simply treated as a rigid plate. It was assumed that all contact interactions were frictionless and there was no penetration.

4.6 Characterization and measurement

The surface morphology of insect antennae, the microstructural characteristics of PVA/ H_3PO_4 ionic gel film and the surface morphology of fiber fabric modified by IL were characterized using SEM (SU8600, HITACHI) and ultra-deep field microscopy (VHX-6000, Japan). Elemental distribution on the IL-treated fabric surface was analyzed via EDS (Octane ED-30, AMETEK), providing insight into the spatial localization of constituent elements. The changes of surface functional groups of the fabric before and after ion

modification were analyzed by FTIR (IS5, Thermo Fisher Scientific). To assess the performance of the sensor, a universal mechanical testing machine (ZQ-990B) was utilized to apply different pressures to the sensor sample, and an LCR meter (IM3536, HIOKI) monitored the corresponding capacitance responses at a frequency of 1 kHz. Response/recovery times follow the T90/T10 standards.

Electronic Supplementary Material: Supplementary material (SEM imaging, ultra-deep field microscopy imaging, EDS measurement, and FTIR measurement) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908992>.

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 upon request.

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Declaration of competing interest

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

Author contribution statement

L. L. L.: Data curation, writing manuscript, experimental design, visualization, validation. J. Q. Z.: Data curation, project administration, writing review and editing, funding acquisition, supervision, validation. J. C. W.: Visualization, investigation. D. K. W.: Investigation. Y. C.: Data curation. S. Q. M.: Resources. X. C. M.: Visualization. X. P. Z.: Investigation. X. Y. L.: Visualization. K. H. Z.: Investigation. W. T. D.: Investigation. J. R.: Investigation. H. H. X.: Investigation. J. M. L.: Investigation. Z. Z. M.: Supervision. Z. W.: Investigation. H. L. S.: Investigation. B. L.: Investigation. T. S.: Supervision, investigation. Z. W. H.: Resources, project administration, funding acquisition. L. Q. R.: Conceptualization, resources. All the authors have approved the final manuscript.

Use of AI statement

None.

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