

Self-adaptive magnetically force-sensitive electronic skin based on biomimetic conductive network structure

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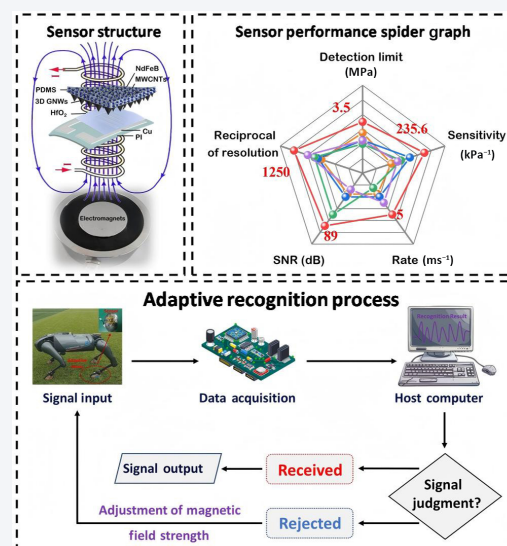
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 Cite this article: Nano Research, 2026, 19, 94908965. <https://doi.org/10.26599/NR.2026.94908965>

ABSTRACT: Haptic perception poses a critical challenge for machine intelligence, as current electronic skins (e-skins) fail to simultaneously achieve high sensitivity, tunable force-sensing properties, and environmental adaptability. Inspired by the human tactile neural network, a flexible e-skin solution based on a biomimetic adaptive mechanism is proposed. By emulating the gating behavior of PZ protein ion channels in Merkel cells, we developed a carbon-based microstructured magneto-responsive force-sensing material (GR-MP-MRE). Leveraging the magnetically induced chaining of NdFeB microparticles and the conductive tunneling gap of multi-walled carbon nanotubes (MWCNTs), a dynamically reconfigurable “island–bridge” network was constructed. This network forms neural synapse-like topological pathways under electromagnetic coupling, enabling dynamic tuning of sensor sensitivity, resolution, and signal-to-noise ratio (SNR) with magnetic fields. When integrated into a robotic dog’s paw, the skin intelligently recognizes complex terrain features and distinguishes microscopic differences, offering a novel approach for biomimetic adaptive design in flexible electronics.



KEYWORDS: GR-MP-MRE, biomimetic conductive network, electronic skin, adaptive recognition, intelligent regulation

1 Introduction

With the rapid advancement of modern technology and materials science [1–5], flexible electronic devices have demonstrated tremendous application potential in healthcare [6–8], defense and military engineering [9, 10], and artificial intelligence [11–17]. Among them, electronic skin (e-skin), a tactile device mimicking human skin functions, has emerged as a key technology for intelligent perception in robotics [18–20]. By establishing tactile channels, e-skins not only serve as a bridge for

human–machine–object interaction but also endows robots with real-time perception capabilities for tactile information such as shape, texture, and material properties. However, existing e-skins are limited by their single force-sensing characteristics, fixed conductive states, and passive response mechanisms, making it difficult to simulate the efficient active tactile perception and self-feedback regulation capabilities of human skin in complex dynamic scenarios. Existing researches still focus on improving the performance of the devices. Wang et al. developed a highly sensitive pressure sensor based on the piezoresistive effect at the semiconductor/conductor interface, exhibiting a sensitivity of 514 kPa⁻¹ [21]. Zang et al. utilized a flexible suspended-gate organic thin-film transistor (SGOTFT) as a demonstration platform for ultra-sensitive pressure detection, achieving an unprecedented sensitivity of 192 Pa⁻¹ and a low detection limit pressure of less than

Received: April 10, 2026; Revised: June 22, 2026

Accepted: June 23, 2026

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0.5 Pa [22]. Cao et al. reported a bio-inspired skin-like material capable of autonomous self-healing in both dry and humid environments, with adjustable ionic conductivity up to $10^{-3} \text{ S}\cdot\text{cm}^{-1}$ and the ability to withstand strains up to 2000% [23]. Although these sensors possess characteristics such as rapid response, high sensitivity, or large range, they are unable to dynamically adjust sensing parameters based on changes in the modulus of contacted objects. This technological gap makes it difficult for e-skins to maintain high precision and stability, when faced with objects of different materials, roughness, and hardness [24–26]. Therefore, how to endow tactile sensors with adaptive sensing capabilities, enabling them to respond to environmental changes in real time and dynamically adjust sensing characteristics, has become an urgent scientific problem.

Adaptive sensing technology, which adjusts perception strategies in real time to adapt to diverse environments, has made significant progress in taste, vision, and auditory domains. For example, in the food industry, it mimics the human taste system to achieve personalized flavor adjustments [27]; in machine vision, it enables autonomous driving navigation through real-time perception of image features [28]; and in intelligent audio processing, it enhances speech clarity through noise suppression [29]. However, in the field of tactile sensing, research on external environmental adaptability remains lacking. In general, the performance of e-skin is related to typical physical parameters of sensitive materials, such as the conductivity, modulus, and size. Conductivity serves as the foundation for e-skins to achieve signal transmission. Highly conductive materials can ensure the rapid and accurate transmission of electrical signals, thereby enhancing the response speed and sensitivity of the devices [30]. For instance, metal and carbon nanomaterials are often employed as sensitive electrodes in sensors due to their high conductivity and high mechanical reliability. Modulus, a key parameter for measuring the “hardness or softness” of materials, has a decisive impact on the flexibility and stretchability of e-skins [31, 32]. For example, polydimethylsiloxane (PDMS), with its low Young’s modulus and excellent biocompatibility, can better adapt to the dynamic changes on the surface of robots. Therefore, establishing a control mechanism that links material physical parameters to device performance is particularly crucial. By developing force-responsive smart materials with tunable moduli and fabricating elastic microstructures with adaptive conductive states [33–36], one can systematically analyze the impact of key parameters such as material modulus on device performance, thereby achieving precise parameter control and performance optimization [37–40].

Here, we propose a strategy for flexible e-skins based on a biomimetic adaptive mechanism. By integrating multi-walled carbon nanotubes (MWCNTs)-NdFeB-PDMS composite magnetorheological elastomers (MREs) with multi-level pyramid graphene nanowalls (GR-MP), a magnetic-field-controllable force-sensitive GR-MP-MRE material is developed. Under the influence of a magnetic field, this material utilizes the chain-like arrangement of NdFeB microparticles and the tunneling conductivity of MWCNTs to form a reconfigurable topological conductive network akin to neural synapses. It can achieve optimal force-sensitive performance across a wide range (1 Pa–3.5 MPa) by adjusting the external magnetic field according to the physical properties of the touched objects. The device exhibits a maximum sensitivity of 235.6 kPa^{-1} , a resolution of 1/1250, and an optimal signal-to-noise ratio (SNR) of 89 dB, along with fast response (10 ms) and high

stability (> 10,000 cycles). When integrated into the paw pads of a robotic dog, this e-skin device can adaptively recognize complex terrain features and distinguish microscopic differences within the same terrain, achieving an accuracy rate up to 99.21%. This study combines the dynamic regulation mechanism of biological tactile neural networks with magneto-responsive microstructured materials, providing a novel biomimetic paradigm for the intelligent development of robotic tactile perception systems.

2 Experimental

2.1 Materials

Silicon wafers (single-side polished with oxide layer) were provided by Zhejiang Lijing Silicon Materials Co., Ltd. Photoresist (S1805) and developer (AZ300) were supplied by Suzhou Ruicai Semiconductor Co., Ltd. Anhydrous ethanol, potassium hydroxide, isopropyl alcohol (IPA), and acetone were obtained from Chongqing Chuandong Chemical Co., Ltd. PDMS (Sylgard 184) was sourced from DOWSIL (USA). Polyimide (PI) hard film was provided by Hongfan Plastic Industry Co., Ltd. MWCNTs ($\geq 99.9999\%$) were supplied by Suzhou Tanfeng Technology Co., Ltd. Neodymium-iron-boron (NdFeB) magnets were provided by Hebei Chaoyue Metal Alloy Materials Co., Ltd.

2.2 Equipment

A laser cutting machine (BL-868) for silicon wafer dicing was purchased from Wuxi Biaolong Laser Technology Co., Ltd. An ultrasonic cleaner (SB25-12 DTD) for ultrasonic degassing was obtained from Ningbo Xinchu Biotechnology Co., Ltd. A binary exposure machine (ABM/6/350/NUV/DCC) from Beijing Zhuoli Hanguang Instrument Co., Ltd. and a reactive ion etcher (Filmlab-R100) from Beijing Plasma Technology Co., Ltd. were used for micro-nano fabrication of multi-level pyramid silicon molds. A plasma-enhanced chemical vapor deposition (PECVD) tubular furnace (BEQ-RF-1200C) from Anhui Beiyike Company was employed for graphene growth. An atomic layer deposition (ALD) system (Savannah 200) from Keysight Technologies was used for hafnium oxide (HfO_2) film deposition. A scanning electron microscope (JSM-7800F) from JEOL Ltd. was utilized to observe the force-sensitive structure of the device. NdFeB permanent magnets and heating pads for magnetic chaining were sourced from Shenzhen Meixia Magnetics Co., Ltd. and Jiukou Hardware Co., Ltd., respectively. An electromagnet (LSD-P25/11) for regulating the external magnetic field was obtained from Hengyun Electromagnet Manufacturer. A high-vacuum magnetron sputtering coater (JCP500) from Beijing Technol Science & Technology Co., Ltd. was used for circuit patterning. A 2450 digital source meter from Giga-tronics was employed for sensor performance measurement. FS-Pro semiconductor parameter test system from ProPlus Design Solutions Inc. was used for device noise testing. Different ground samples (sandy ground, lawn, plastic ground, and tiled ground) for adaptive recognition applications were purchased from Langya Home Store. The Cyberdog robotic dog for adaptive recognition applications was obtained from Xiaomi.

2.3 MRE fabrication method

During MRE preparation, to confirm the material properties, the effects of different ratios of filler materials (NdFeB and MWCNTs)

and matrix material (PDMS) on device performance were explored. It was found that the PDMS mixing ratio also affected the sensitivity and detection range of the device. The results showed that the ratio of 10:1 provided the best sensitivity and the widest measurement range, as shown in Fig. S1 in the Electronic Supplementary Material (ESM). A performance comparison table (Table S1 in the ESM) for sensors with different filler material ratios was also prepared. The experimental results indicated that the formulation with 10% NdFeB, 2% MWCNTs, and 10% PDMS exhibited the best performance. Therefore, in this study, we adopted a PDMS ratio of 10:1 as the flexible matrix material and a material composition of 10% NdFeB, 2% MWCNTs, and 10% PDMS.

First, 14.545 g of PDMS component A (10% volume fraction) and 0.32 g (2% volume fraction) of MWCNTs (length: 2–3 μm , and width: 30–50 nm) were added sequentially to a beaker and stirred at room temperature for 20 min. The mixture was then subjected to vacuum degassing for 30 min in a vacuum chamber and ultrasonic cleaning for 15 min in an ultrasonic cleaner to remove bubbles. Subsequently, 11.63 g (10% volume fraction) of 2000-mesh NdFeB powder (diameter: 4–5 μm) was added, and the stirring, vacuum degassing, and ultrasonic cleaning steps were repeated. Finally, 1.455 g of PDMS component B (10% volume fraction) was added, and the stirring, vacuum degassing, and ultrasonic cleaning steps were repeated again to obtain the composite MRE.

2.4 Silicon mold fabrication method

The fabrication of multi-level pyramid silicon molds primarily involved two steps: photolithography and etching. First, silicon wafers were cut into 2 cm $\times$ 2 cm squares using a laser cutting machine. The cut silicon wafers were ultrasonically cleaned in deionized water, acetone, and anhydrous ethanol for 15 min each to remove surface impurities (which could affect the uniformity of the photoresist). S1805 photoresist was spin-coated onto the treated silicon wafers (parameters: 500 rpm for 5 s, 5000 rpm for 25 s, and 5500 rpm for 5 s) and then dried on a 100 $^{\circ}\text{C}$ hot plate for 10 min. The wafers were exposed using a binary exposure machine (exposure power: 3 mW/cm²) for 8.5 s and then developed in AZ300 developer for 30 s. After photolithography, square patterns formed on the silicon wafers, with the silicon dioxide layer within the patterns exposed on the surface. The exposed silicon dioxide was etched using an reactive ion etching (RIE) dry etcher with trifluoromethane (CHF₃) etching gas (flow rate: 40 sccm, etching power: 100 W, and etching rate: 25 nm/min) for 15 min. Subsequently, the photoresist was removed by ultrasonic cleaning in acetone, and the sample surface was cleaned by ultrasonic cleaning in alcohol to expose the Si in the square holes. Pyramid structures were obtained through anisotropic etching of the silicon wafers using KOH. The etching solution (KOH:IPA:H₂O = 2.89 g:15 mL:50 mL) was heated for 30 min in a constant-temperature water bath at 80 $^{\circ}\text{C}$. Finally, the etched silicon wafers were rinsed with deionized water and blown dry under high-purity nitrogen to obtain silicon molds with multi-level inverted pyramid structures.

2.5 Device fabrication method

First, the prepared microstructured silicon mold was placed in a quartz tube, and a graphene carbon nanofilm was grown on the silicon surface using PECVD. Next, the prepared composite MRE was coated onto the surface of the multi-level pyramid silicon mold and placed on a 500 mT NdFeB permanent magnet and an 80 $^{\circ}\text{C}$

heating pad for 1 h to induce magnetic chaining. It was then magnetized under a 500 mT magnetic field for 50 min. Afterward, the MRE was peeled off from the silicon mold to obtain a 1.5 mm thick and intelligently tunable GR-MP-MRE force-sensitive layer, which was then cut into 1 cm $\times$ 1 cm squares. For the bottom electrode, copper interdigitated patterns were magnetron sputtered onto a PI substrate to form flexible printed circuit (FPC), with its physical image and design shown in Fig. S2 in the ESM. A 5 nm HfO₂ film was deposited onto the FPC using ALD. Finally, the force-sensitive layer and the FPC were encapsulated using electrostatic adhesion to maintain the device's good initial state.

3 Results and discussion

3.1 Design and fabrication of sensor

The human tactile neural network is an efficient and intelligent sensory system that can highly sensitively perceive external tactile stimuli through the gating effects of PZ protein ion channels in Merkel cells. Signals are efficiently transmitted as neural potential signals through synapses between neuronal cells. Inspired by this process, the adaptive biomimetic mechanism skillfully integrates biological principles into engineering technology by simulating the human neural network to construct a magneto-responsive “island–bridge” interconnected conductive structure, forming an adaptive conductive network, as illustrated in Fig. 1(a). Under the influence of a magnetic field during the preparation process, NdFeB microparticles form ordered chain-like arrangements along the magnetic field direction. The nanoscale diameter and high aspect ratio of carbon nanotubes (CNTs) enable the CNT network to exhibit both macroscopic percolation characteristics and microscopic tunneling effect conductivity. The active sites formed through electron tunneling and local field enhancement effects between MWCNTs linked on the surfaces of magnetic microparticles can spontaneously establish signal transmission pathways, a process analogous to the gating behavior of PZ protein ion channels under external stimuli. Under electromagnetic field coupling, these pathways further form a highly complex topological network structure, similar to synaptic connections in the human neural network. Ultimately, this achieves the goal of dynamically tuning various force-sensing properties of the sensor with the magnetic field, thereby simulating the self-feedback regulation function of real skin.

Piezoresistive sensors have garnered significant attention from numerous researchers due to their diverse structural designs, flexible output signals, low fabrication costs, and suitability for tunable force-sensing properties. Figure 1(b) depicts a structural schematic of a novel flexible and adaptive electronic skin capable of intelligent tuning of various force-sensing properties under a magnetic field. The top force-sensitive electrode consists of a conformal graphene nanowall (GNWs) thin film on the surface of multilevel micro-pyramids of MRE substrate. The irregular microstructures possess a certain preload, enhancing the sensitivity and response speed of the tactile sensor while also improving its stability, forming an intelligently tunable force-sensitive GR-MP-MRE layer. The bottom layer comprises a 5 nm ultrathin HfO₂ layer and a flexible interdigitated copper electrode FPC. Specific details regarding the electromagnet model and specifications are provided in Table S2 in the ESM. This sensor was integrated into shoes and applied to a robotic dog for terrain recognition scenarios,

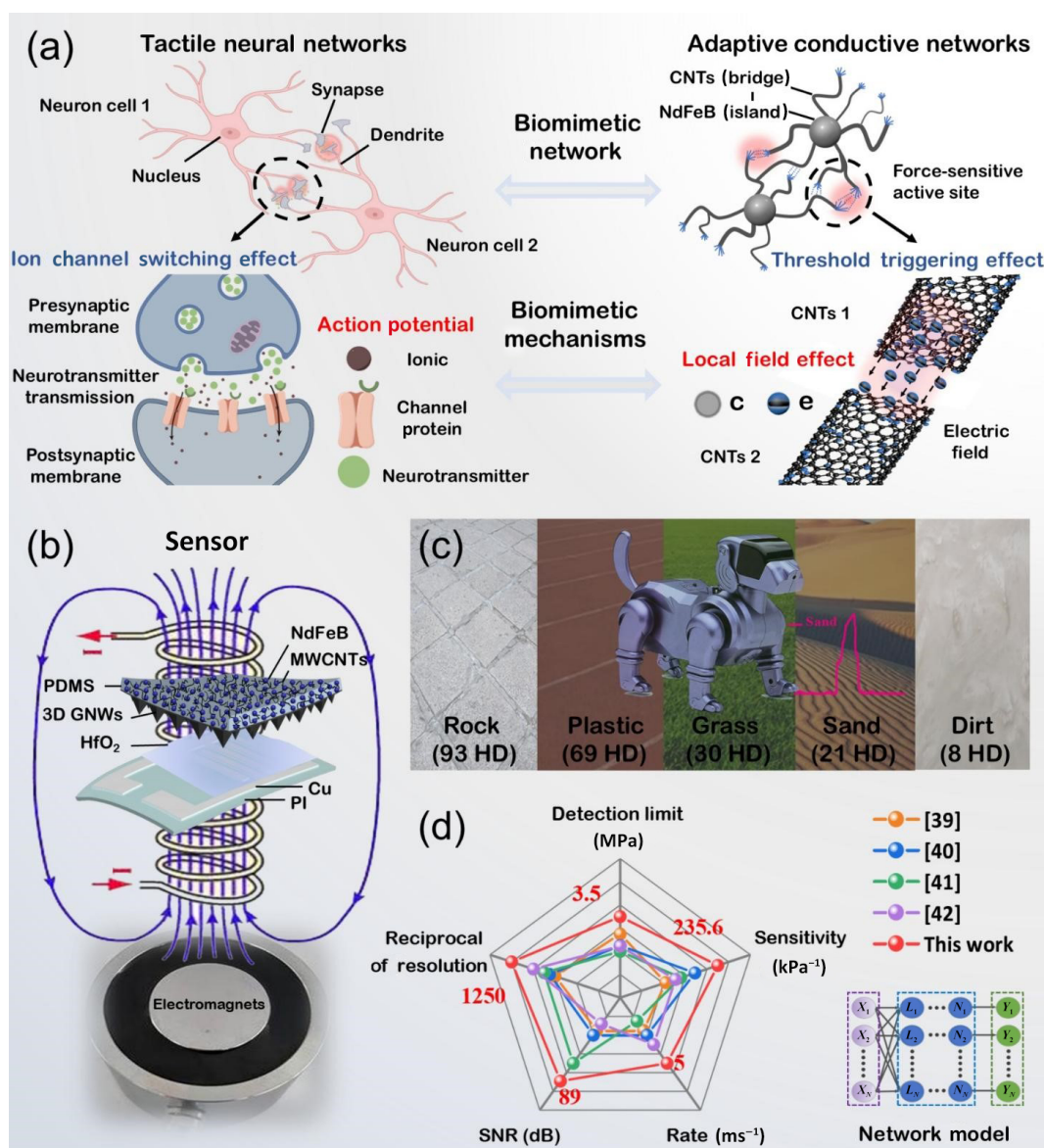


Figure 1 Schematic diagram of the tactile system for adaptive electronic skin. (a) Schematic illustration of the biomimetic mechanism. (b) Device structure under magnetic field. (c) A mechanical dog with adaptive tactile sensors on its feet, which could recognize different terrain environments. (d) Spider web plot comparing the performance of tactile devices.

as shown in Fig. 1(c). Furthermore, compared with other reported similar sensors, as shown in the spider plot in Fig. 1(d), our device demonstrates superior performance across all five dimensions: sensitivity, measurement range, SNR, resolution, and response rate. In contrast, similar devices typically exhibit performance advantages in only one dimension. Compared with other recently reported adaptive or tunable sensors, the active control mechanisms in Refs. [41, 42] rely on microstructural reconstruction or remain at the simulation stage; the pneumatic regulation in Ref. [43] has limitations in response speed and control accuracy; and the mechanical preloading in Ref. [44] suffers from low sensitivity. In contrast, our device organically combines active external magnetic control with an “island–bridge” structure in the composite material, achieving optimized performance across the entire pressure range from low to high, along with non-contact fast response, higher dynamic tunability, and enhanced engineering practicality. The multilevel pyramid structure consists of alternating layers of small

pyramids (with a spacing of 5 μm) and a mix of large and small pyramids (with a spacing of 2.5 μm). The specific dimensions are large pyramids (10 $\mu\text{m} \times 10 \mu\text{m}$) and small pyramids (5 $\mu\text{m} \times 5 \mu\text{m}$), with a distance of 10 μm between pyramid tips. The entire sensor contains approximately one million pyramid microarrays. To achieve adaptive recognition and imaging of different geographical environments, the sensor is connected to an analog-to-digital converter (ADC) with a bluetooth computer interface, as shown in the photograph in Fig. S3 in the ESM.

Figure 2(a) provides a detailed depiction of the sensor fabrication process. Initially, a silicon mold with a multilevel inverted pyramid structure was prepared using photolithography techniques, including exposure, development, dry etching, and wet etching. Subsequently, the mold was placed in a tubular furnace, and conformal three-dimensional (3D) GNWs were grown using PECVD for the GR-MP mold. A top-view scanning electron microscopy (SEM) image of the mold is shown in Fig. 2(b),

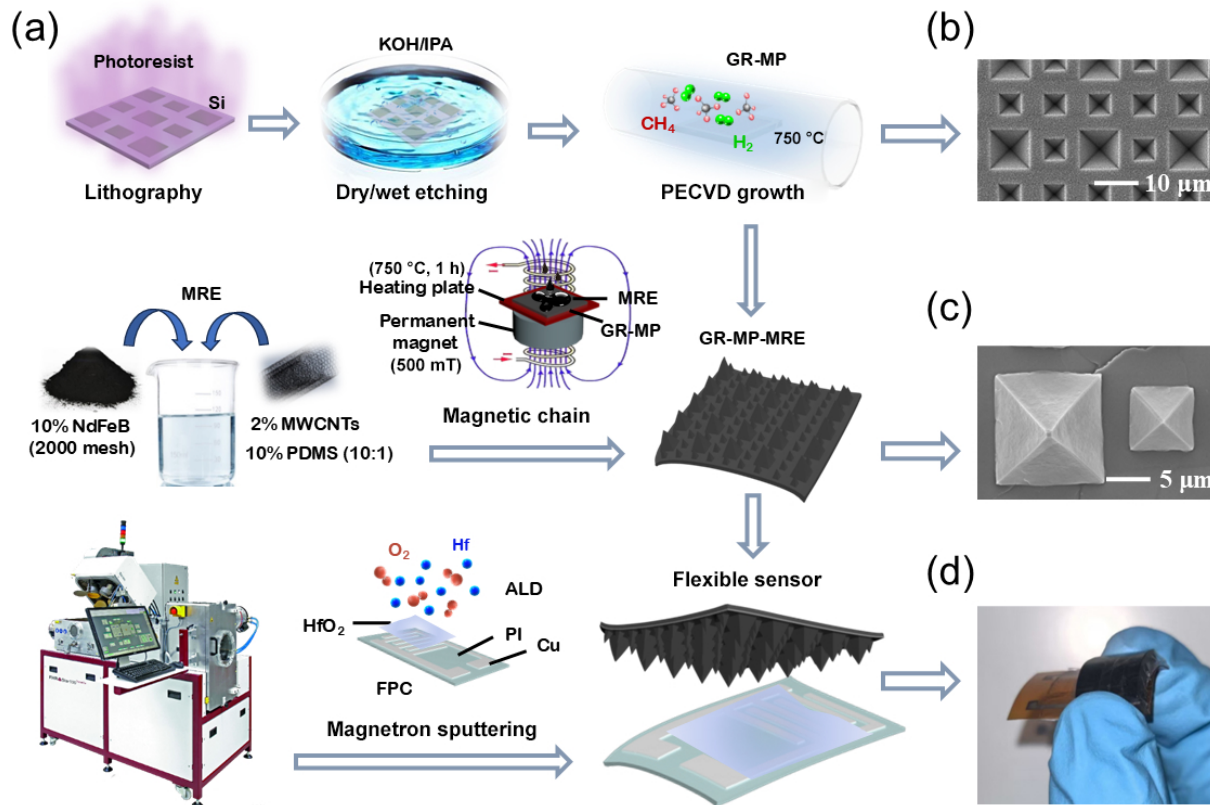


Figure 2 Preparation of tactile sensor. (a) Schematic illustration of the device fabrication process. (b) SEM image of the mold surface for GR-MP, scale bar: 10 μm. (c) SEM image of the surface of the intelligently tunable force-sensitive GR-MP-MRE layer, scale bar: 5 μm. (d) Photograph of the sensor.

revealing the deposition of three-dimensional GNWs on the surface of the inverted cone-shaped silicon mold. And then, the curable magnetorheological fluid was poured into the GR-MP mold. Under the influence of the magnetic field, NdFeB microparticles were arranged in a chain-like pattern to form MRE. After transfer, the tunable force-sensitive GR-MP-MRE layer was obtained, as shown in Fig. 2(c). This layer was subsequently integrated with the bottom electrode of FPC, which had been deposited with an HfO₂ layer. Finally, the device was encapsulated using electrostatic adhesion. A photograph of the sensor is shown in Fig. 2(d). The detailed steps and parameters of the sensor fabrication process are fully described in the sensor fabrication methods section of the experimental procedures.

3.2 Sensing mechanism of sensors

During material preparation, the magnetorheological effect causes magnetic particles within the MRE to align along the magnetic field direction, forming chain-like structures that significantly influence the material's electrical conductivity [45–49]. Figure 3(a) displays SEM images and energy dispersive X-ray spectroscopy (EDS) spectrum of the MRE. Figure 3(a)(I) shows the MRE with magneto-induced chaining, where ordered chains of magnetic particles are observed along the magnetic field direction. In contrast, the SEM image without magneto-induced chaining, as shown in Fig. S4 in the ESM, reveals a disordered arrangement of magnetic particles. Figure 3(a)(II) is an enlarged SEM image of the magnetic particles in Fig. 3(a)(I), showcasing the distribution of carbon nanotubes around NdFeB microparticles. It can be observed that multiple carbon nanotubes aggregate around the NdFeB magnetic particles, forming active sites between MWCNTs. The SEM image of NdFeB

microparticles without added carbon nanotubes, as shown in Fig. S5 in the ESM, exhibits a similar morphology to that with carbon nanotubes. Figure 3(a)(III) is an EDS spectrum of the area in Fig. 3(a)(II), with the highest contents of Fe and Nd, indicating that this particle might correspond to NdFeB magnetic particles. Point scans were performed on the carbon nanotubes and NdFeB microparticles at the positions indicated in Fig. 3(a)(II), and the EDS results are shown in Fig. S6 in the ESM. Carbon nanotubes randomly form force-sensitive active sites on the surface of magnetic nanoparticles, thereby constructing a highly complex and ordered force-sensitive conductive network structure resembling neural synapses. A local field enhancement effect occurs at the active sites, where the current density exhibits an exponential relationship with the distance change induced by elastomer strain, expressed as [50]

$$E_{\text{loc}} = \beta \cdot E_0 = \beta \cdot \frac{V}{d} \quad (1)$$

where E_{loc} represents the local electric field intensity near the carbon nanotube, E_0 denotes the applied uniform electric field, β is the field enhancement factor, a dimensionless parameter used to describe the degree of electric field enhancement near the carbon nanotube, V represents the applied voltage, and d indicates the distance between the electrode plates.

As the field effect intensifies, electrons can tunnel between the tube walls, expressed as [51]

$$J = \frac{1.56 \times 10^{-6} E_{\text{loc}}^2}{\varphi} \exp\left(-\frac{6.83 \times 10^7}{E_{\text{loc}}} \varphi^{3/2}\right) \quad (2)$$

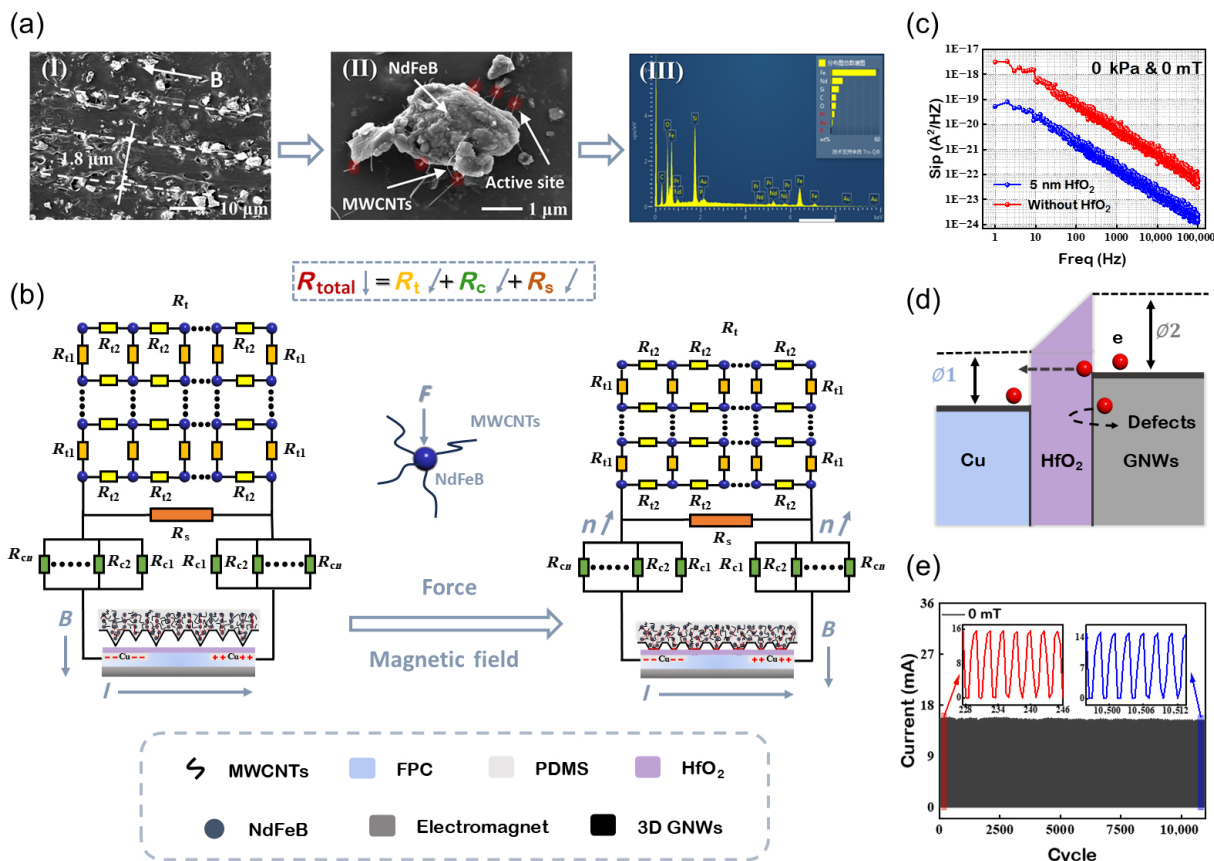


Figure 3 Sensing principles of e-skins. (a) SEM images and EDS maps of MRE. (I) Showing the MRE after magneto-induced chaining, with a scale bar of 10 μm ; (II) depicting the distribution of MWCNTs around NdFeB particles, with a scale bar of 1 μm ; and (III) presenting the EDS map of the area in (II). (b) Schematic illustration of the sensing principle of the flexible and adaptive electronic skin. (c) Comparison of noise signals between devices with and without an HfO_2 layer under conditions of no magnetic field and no applied pressure. (d) Noise suppression mechanism of HfO_2 tunneling layer. (e) Current variation during over 10,000 loading/unloading cycles at 20 kPa.

where J represents the field emission current density, and ϕ (work function) represents the minimum energy required for an electron to escape from the material surface. The application of stress strain can further activate additional active sites, increasing the probability of electron tunneling between carbon nanotubes. This reduces the bulk resistance R_t of the force-sensitive layer GR-MP-MRE, significantly improving its conductance response [52]. Additionally, the length of the MWCNTs employed in this experiment is approximately 2.5 μm . It has been found that when the inter-link spacing exceeds the average length of MWCNTs, the probability and number of randomly formed conductive links decrease. Therefore, maintaining an appropriate inter-link spacing is crucial for constructing an optimal conductive network. In this experiment, by adjusting the NdFeB content (with a volume fraction of 2%), we controlled the inter-link spacing to be close to the length of MWCNTs, approximately 2 μm . NdFeB magnetic particles were utilized as nodes, with MWCNTs serving as bridges connecting adjacent nodes, thereby forming a three-dimensional spatial conductive network. Figure 3(b) provides a detailed explanation of the sensing mechanism through an equivalent circuit diagram. The working principle primarily relies on the piezoresistive effect, with the core being the conversion of external mechanical stress into changes in the resistance value of the sensing element, which is subsequently translated into an electrical signal output. In this device, R_t , R_c , and R_s are connected in series, and the total resistance can be expressed as

$$R_{\text{total}} = R_t + R_c + R_s \quad (3)$$

where R_t represents the bulk resistance of the force-sensitive GR-MP-MRE layer, R_c denotes the contact resistance between the force-sensitive GR-MP-MRE layer and the Cu interdigitated electrodes on the FPC board, and R_s is the resistance of the GNWs. The variation in R_s is relatively small and can be neglected. The change in the device's resistance primarily relies on the variations in the bulk resistance R_t and the contact resistance R_c . Under no pressure, the irregular multi-level pyramid microstructure minimizes contact area with the HfO_2 surface, keeping the initial current at a low level. Under low pressure, the interfacial contact resistance R_c dominates. As pressure increases, the microstructure undergoes elastic deformation, concentrating pressure and strain at the tip. This expands the conductive area between the pyramid apex and the bottom electrode [53], leading to a significant increase in tunneling current [54]. The number n of contact points will increase. Since the contact resistance is composed of n parallel R_c resistors, the value of contact resistance will decrease. Under high pressure, the overall strain of the multi-level pyramid structure reaches saturation, and the contact area will no longer increase. At this point, the bulk resistance R_t becomes the dominant factor. As pressure increases, the elastic body undergoes compressive deformation, shortening the spacing of longitudinal bulk resistors R_{ti} . This increases tunneling current through active sites and, more significantly, triggers additional active sites, further reducing R_t .

Consequently, across the full pressure range, the device's total resistance decreases with increasing mechanical stress, leading to a corresponding increase in current output.

Furthermore, to suppress the intrinsic noise generated during the piezoresistive response process at the device interface, an ultrathin HfO_2 tunneling barrier layer between the FPC sensing electrode and the pyramidal microstructure is introduced. Figure 3(c) illustrates a comparison of noise signals for devices with and without the HfO_2 layer under conditions of no magnetic field and no pressure. It is evident that the noise level in devices with the HfO_2 layer is significantly lower than that in devices without it. Figure 3(d) illustrates that within the sensor mechanism, the cause of noise lies in the non-deterministic capture and release of charge carriers by defects. The HfO_2 layer acts as a high-energy barrier, requiring greater energy expenditure for low-energy carriers released from

traps to traverse this barrier and generate noise current. Consequently, noise current experiences significantly stronger suppression compared to signal current, thereby reducing reliance on subsequent noise reduction algorithms [55]. Figure 3(e) demonstrates that the sensor exhibits stable signals during over 10,000 loading and unloading cycles at a pressure of 20 kPa, indicating remarkable durability.

3.3 Sensor performance testing

To investigate the relationship between the device's sensitivity and variations in magnetic field intensity, we tested the sensor's response to pressure under different magnetic fields, and the normalized current curves and their corresponding sensitivity fitting plots of the sensor are shown in Fig. 4(a). During the first stage (1 Pa–10 kPa), the device exhibits high sensitivity, which

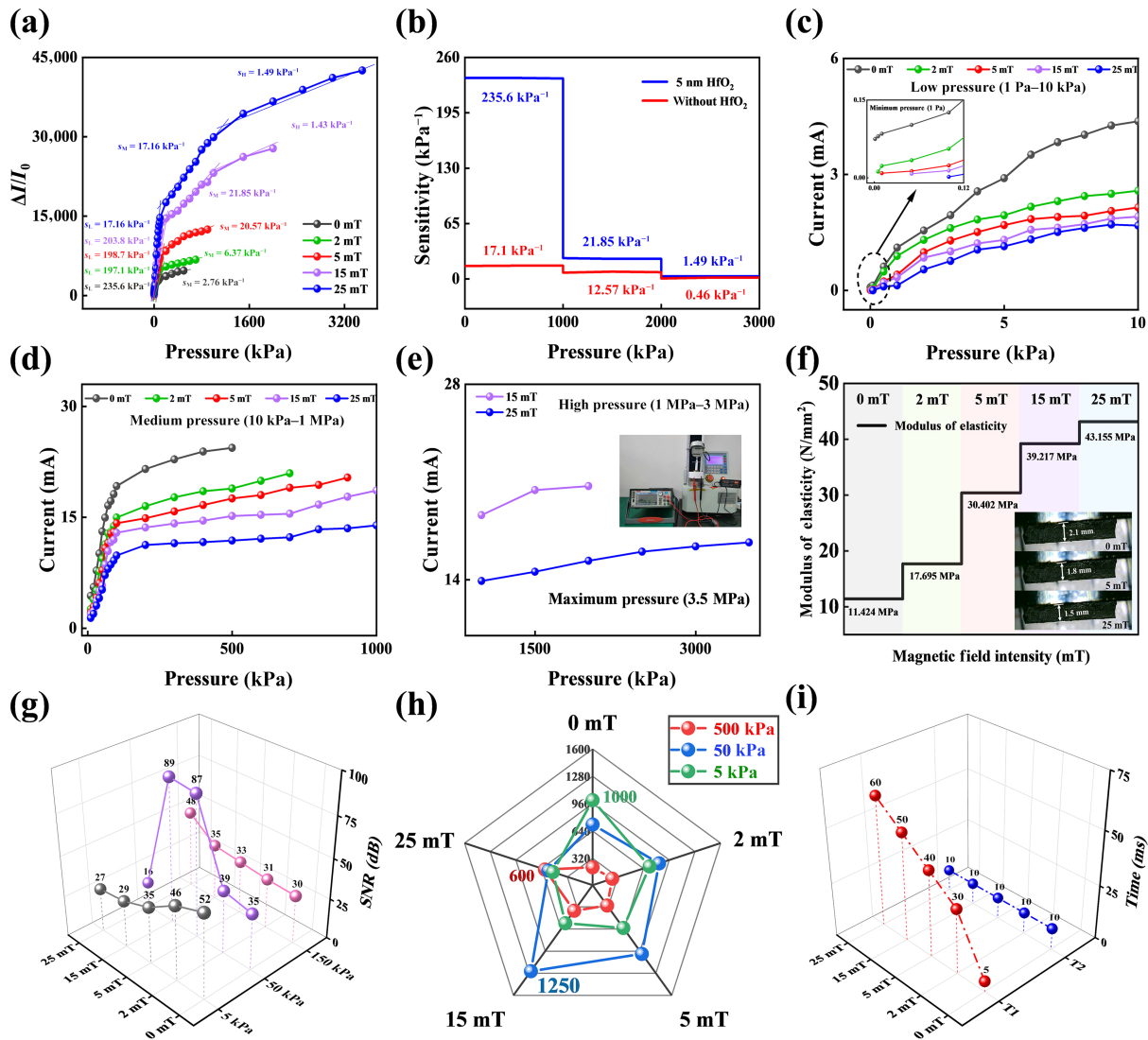


Figure 4 Performance profile of e-skin. (a) Under magnetic fields of 0, 2, 5, 15, and 25 mT, normalized current curve of optimized flexible sensor with pressure and fitted sensitivity of the sensor (ranging from 1 Pa to 3.5 MPa). (b) Comparison of the optimal sensitivity performance of devices with and without an HfO_2 layer in low, medium, and high-pressure regimes. (c) Current response curves under low pressures (1 Pa–10 kPa), with the inset in the top-left corner showing a zoomed-in view of the current response curve within the pressure range of 0–0.1 kPa. (d) Current response curves in the medium pressure range (10 kPa–1 MPa). (e) Current response curves under high pressures (1 MPa–3.5 MPa), with the inset showing an actual scene image during device testing. (f) Variations in the elastic modulus of MRE under different magnetic fields, with the inset being an optical microscope image comparing the cross-sectional thicknesses of the MRE under different magnetic fields. ((g) and (h)) The changes in the SNR and the reciprocal of sensor's resolution under different magnetic fields when pressures of 5, 50, and 150 kPa are applied. (i) Variations in the response time and recovery time of the sensor under different magnetic fields.

increases with magnetic field strength. However, the peak sensitivity of 235.6 kPa^{-1} occurs at 0 mT, making it suitable for detecting minute pressure changes. In the second stage (10 kPa–1 MPa), the device sensitivity first increases and then decreases with magnetic field strength. The optimal sensitivity is achieved at 15 mT, reaching 21.85 kPa^{-1} , making it suitable for detecting medium pressures. In the third stage (1 MPa–3.5 MPa), device sensitivity increases with magnetic field strength, reaching an optimal sensitivity of 1.49 kPa^{-1} at 25 mT, making it suitable for detecting high-intensity pressures. The results demonstrate that under different pressure conditions, the device can achieve optimal response performance through magnetic regulation. The linearity of the device under full scale can be divided into two linear intervals. Specifically, it exhibits a segmented response across different pressure ranges. In the first stage, under a pressure of 0–100 kPa, the linearity for different magnetic field gradients is approximately 0.98, as shown in Fig. S7 in the ESM. In the second stage, under a pressure of 100–3500 kPa, the linearity is approximately 0.95, as shown in Fig. S8 in the ESM. The device maintains high linearity across both pressure detection ranges. Furthermore, we investigated the influence of an ultrathin HfO_2 layer on the device's force-sensing performance. As shown in Fig. 4(b), the sensitivity of devices with an HfO_2 layer significantly outperformed those without, demonstrating an approximately 14-fold enhancement. This improvement stems from the HfO_2 layer suppressing intrinsic noise, reducing the initial current, and expanding the current variation range. Consequently, a larger change of electrical signal can be generated within the same pressure variation range.

Simultaneously, under an external magnetic field, the elastic materials exhibit a pronounced magnetostrictive contraction effect, leading to an increase in the elastic modulus of the force-sensitive layer and thereby expanding its measurement range in pressure sensing applications. Figures 4(c)–4(e) show the measurement ranges of the device under different magnetic fields, 0 (1 Pa–0.5 MPa), 2 (5 Pa–0.7 MPa), 5 (10 Pa–0.59 MPa), 15 (50 Pa–2 MPa), and 25 mT (100 Pa–3.5 MPa). Changes in the magnetic field induce alterations in the elastic modulus of the MRE material. As shown in Fig. 4(f), the elastic modulus of MRE increases with rising magnetic field strength, with detailed data presented in Table S3 in the ESM. The inset illustrates cross-sectional thickness variations of MRE under different magnetic fields observed via optical microscopy, revealing a gradual decrease in thickness as the magnetic field intensifies.

The trends in the SNR of the sensor under different magnetic fields when subjected to small (5 kPa), medium (50 kPa), and large (150 kPa) pressures are shown in Fig. 4(g), with the raw data presented in Fig. S9 in the ESM. At a pressure of 5 kPa, the interfacial piezoresistive effect dominates. As the magnetic field increases, the material modulus rises, reducing the pyramid deformation. At the same pressure, the contact area decreases, weakening the signal and causing the signal-to-noise ratio to decline. Under high pressure conditions, bulk resistance plays the primary role. As the magnetic field increases, more active sites are triggered, significantly enhancing the device's force-sensitive response signal and leading to an upward trend in the signal-to-noise ratio. At medium pressures, an optimal SNR of 89 dB is achieved between these two effects. The signal-to-noise ratio variation trend for devices without an HfO_2 layer is shown in Fig. S10 in the ESM, consistent with that of devices with an HfO_2 layer, but devices with an HfO_2 layer exhibit a higher SNR.

When subjected to small (5 kPa), medium (50 kPa), and large (150 kPa) pressures under different magnetic fields, the inverse variation of the device resolution is shown in a spider web diagram in Fig. 4(h). Raw data are presented in Fig. S11 in the ESM. It can be observed that under small pressure, the resolution of the sensor decreases with increasing magnetic field, with the optimal resolution achieved at 0 mT, being 1/1000. Under medium pressure, the resolution initially increases and then decreases with the magnetic field, with the optimal resolution occurring at 15 mT, reaching 1/1250. Under large pressure, the resolution increases with the magnetic field, and the optimal resolution is 1/600 at 25 mT.

The resolution variation with magnetic field at different pressures aligns with the variation pattern of the device's SNR under magnetic field. This sensor exhibits relatively fast dynamic response under varying magnetic fields, as measured by rapidly applying and releasing 20 g of pressure. The response time ranges from 5 to 60 ms, while the recovery time is approximately 10 ms, as shown in Fig. 4(i). Raw data are presented in Fig. S12 in the ESM. Additionally, the device exhibits excellent dynamic pressure sensing performance (Fig. S13 in the ESM) and remarkable durability (Fig. S14 in the ESM). These superior characteristics offer broad application prospects for our flexible electronic skin device in fields such as robotic tactile sensing.

3.4 Printed circuit board (PCB) board design and host computer development

A specialized PCB for adaptive e-skin applications is designed, and it provides electrical interconnections among various electronic components within devices, facilitating current transmission, signal transfer, and data exchange. Its physical photograph and detailed structural design are shown in Fig. S15 in the ESM.

The host computer is a software application running on a computer that is used for collecting and saving data. To achieve adaptive recognition and visualization of different geographical environments, we developed a dedicated host computer for this device. In this development, we selected long short-term memory (LSTM) as the temporal neural network model. LSTM is a variant of the recurrent neural network (RNN), specifically designed to address the gradient vanishing and gradient explosion problems that traditional RNNs encounter when processing long sequence data. The development process involved identifying five types of geographical terrains (muddy ground, sandy ground, grassy ground, plastic ground, and tiled ground) as targets and integrating the electromagnet voltage values as magnetic field regulation conditions into the signal acquisition circuit. By adjusting the voltage of the PCB circuit board, different magnetic field gradients of the electromagnet can be obtained. Consequently, the host computer displays real-time two-dimensional pressure signal curves and the optimal adaptive recognition results, further deriving the optimal voltage values for recognizing each terrain. Additionally, Python was chosen as the programming language for host computer development. Specific applications were written according to the particular hardware devices and application scenarios to realize functions such as communication with the lower computer, data acquisition, processing, and display.

3.5 Adaptive recognition of ground environments

Currently, the application of sensors in complex environments faces multiple challenges. On the one hand, limitations in measurement range and resolution restrict sensors' accurate perception of diverse

tactile information, such as morphology, material texture, roughness, and hardness. On the other hand, insufficient signal-to-noise ratio affects the accuracy and reliability of tactile data. Furthermore, the limited functionality of sensors restricts their adaptability across diverse environments, making the lack of dynamic tuning capabilities an urgent issue to address. The introduction of tactile adaptation can enhance a sensor's perception capabilities, ensuring robots accurately capture diverse tactile information in complex environments and elevating the intelligence level of machine recognition. Simultaneously, it enhances sensor adaptability, enabling them to adjust performance parameters in response to external environmental changes to maintain optimal perception. Therefore, in practical operations, sensors often require performance tuning based on varying external conditions to better adapt to complex environmental tasks.

In this study, the prepared devices were integrated onto shoes and worn on the four legs of the Xiaomi CyberDog for synchronous data collection, as shown in Figs. S16 and S17 in the ESM. The robotic dog was operated at a speed of 0.3 m/s and a posture height of 30 cm, with data recorded in a sequence from front to back and left to right. A total of 5000 samples were collected, ensuring 200 samples per combination of five terrain types and five voltage values. The sampling frequency was 3000 Hz, with consistent acquisition time and waveform data volume for each sample. The data were divided into training, testing, and validation sets at an ratio of 8:2:2, and the neural network model underwent 200 training iterations. During experiments, test samples were placed at a fixed distance from the robotic dog. The dog first performed a forward walking operation. Upon contact with the sample, it walked a certain distance before executing a stop operation. The mechanical dog navigating indoor tile floors is shown in Movie S1 in the ESM, and its outdoor navigation on a synthetic track is shown in Movie S2 in the ESM. During walking, the sensor recorded signal curves for five distinct ground environments without magnetic fields (Fig. 5(a)). Figure 5(b) demonstrates the device's stable dynamic response during loading/unloading cycles, with consistent signal curves.

The curves depicting the variation patterns of resistance signals across five distinct terrain environments under different magnetic field gradients, as shown in Fig. 5(c), reveal that the device's resistance and SNR exhibit the similar trends under varying magnetic field gradients. When the target current remains constant, increasing the sampling resistance significantly amplifies the signal strength. Although noise intensity also increases, the change is not pronounced. Therefore, the resistance exhibits the same trend as the signal-to-noise ratio (Figs. S18(a)–S18(d) in the ESM). Furthermore, to validate the sensor's ability to distinguish subtle differences within the same terrain type and achieve further adaptive recognition, we also compared recognition rates on lawns of varying depths. As shown in Fig. 5(d), at 2 mT, the optimal recognition rate for dense lawns reached 98.40%, while sparse lawns achieved only 94.86%. At 15 mT, sparse lawns achieved the highest recognition rate of 99.21%, while dense lawns only reached 95.60%. The confusion matrices for recognition accuracy of dense and sparse lawns under different magnetic fields are shown in Figs. S19 and S20 in the ESM.

To further elucidate the underlying mechanism by which magnetic field tuning enhances terrain recognition, we analyzed the SNR, sensitivity, detection range, feature discriminability, and recognition accuracy. When an external magnetic field is applied,

NdFeB microparticles align into chain-like structures along the field direction, while MWCNTs form tunneling conductive paths between the chains, constructing an “island (NdFeB)–bridge (MWCNTs)” network. Variations in magnetic field strength alter the chain density and bridging distance, thereby modulating the overall resistance and its sensitivity to external forces. Specifically, a lower magnetic field (e.g., 5 mT) yields a looser chain structure, providing a larger detection range but lower sensitivity, which is suitable for coarse sensing on hard terrains. In contrast, a higher magnetic field (e.g., 20 mT) enhances chain alignment and reduces the tunneling barrier, resulting in significantly improved sensitivity and SNR, which benefits the detection of subtle pressure signals on soft or textured terrains. The experimental results in Table S4 in the ESM demonstrate that under optimized magnetic fields, the feature discriminability among different terrains is markedly enhanced, with the highest recognition accuracy reaching 97.6%, confirming the effectiveness of magnetic field control in achieving adaptive sensing. In this experiment, due to the varying material mechanical properties (hardness, viscoelasticity, plasticity, and fluidity) of different ground surfaces, distinct input waveform curves were generated during the mechanical dog's stepping process. It is worth noting that, under each magnetic field condition, the optimal classification accuracy is closely related to the SNR and peak distinguishability within the corresponding pressure range. A magnetic field of 0–5 mT is favorable for soft terrain recognition (high sensitivity and SNR of 75–82 dB), while a magnetic field of 15–25 mT is more suitable for hard terrain recognition (wide detection range and SNR of 85–89 dB). This confirms that magnetic tuning enhances classifier performance across different mechanical impedance ranges by optimizing signal-level metrics, particularly SNR and class separability. A variant of the RNN, the LSTM network, was employed to construct the terrain recognition system, outputting five ground surface recognition results (Fig. 5(e)).

Furthermore, the adaptive recognition logic flow of the electronic skin for different ground environments is illustrated in Fig. 6(a). We tested the CyberDog equipped with adaptive shoes on an outdoor lawn, with its walking state depicted in Fig. 6(b). The inset in the top-right corner showcases the actual appearance of the device integrated into the shoe sole. We employed a nonlinear dimensionality reduction algorithm, specifically *t*-distributed stochastic neighbor embedding (*t*-SNE), to systematically process the terrain recognition data, clearly demonstrating five distinct terrain categories (Fig. 6(c)). Analysis results indicate that grassland, as a terrain type with obvious differences, demonstrates excellent clustering performance under varying magnetic field gradients. However, softer terrains such as mud and sand require subtle detection of minute material variations. Under low magnetic fields, these surfaces exhibit higher device sensitivity and optimal clustering performance, which gradually diminishes as magnetic field strength increases. Harder surfaces like plastic and tile require a wider device measurement range. While their clustering performance is suboptimal under weak magnetic fields, both the measurement range and clustering effectiveness significantly improve as the applied magnetic field strength increases. The device achieves its highest recognition accuracy of 99.21% (Fig. 6(d)). Confusion matrices under different magnetic fields are shown in Fig. S21 in the ESM. Furthermore, we measured the latency parameters of key components using our experimental setup and prepared Table S5 in the ESM, which provides quantitative

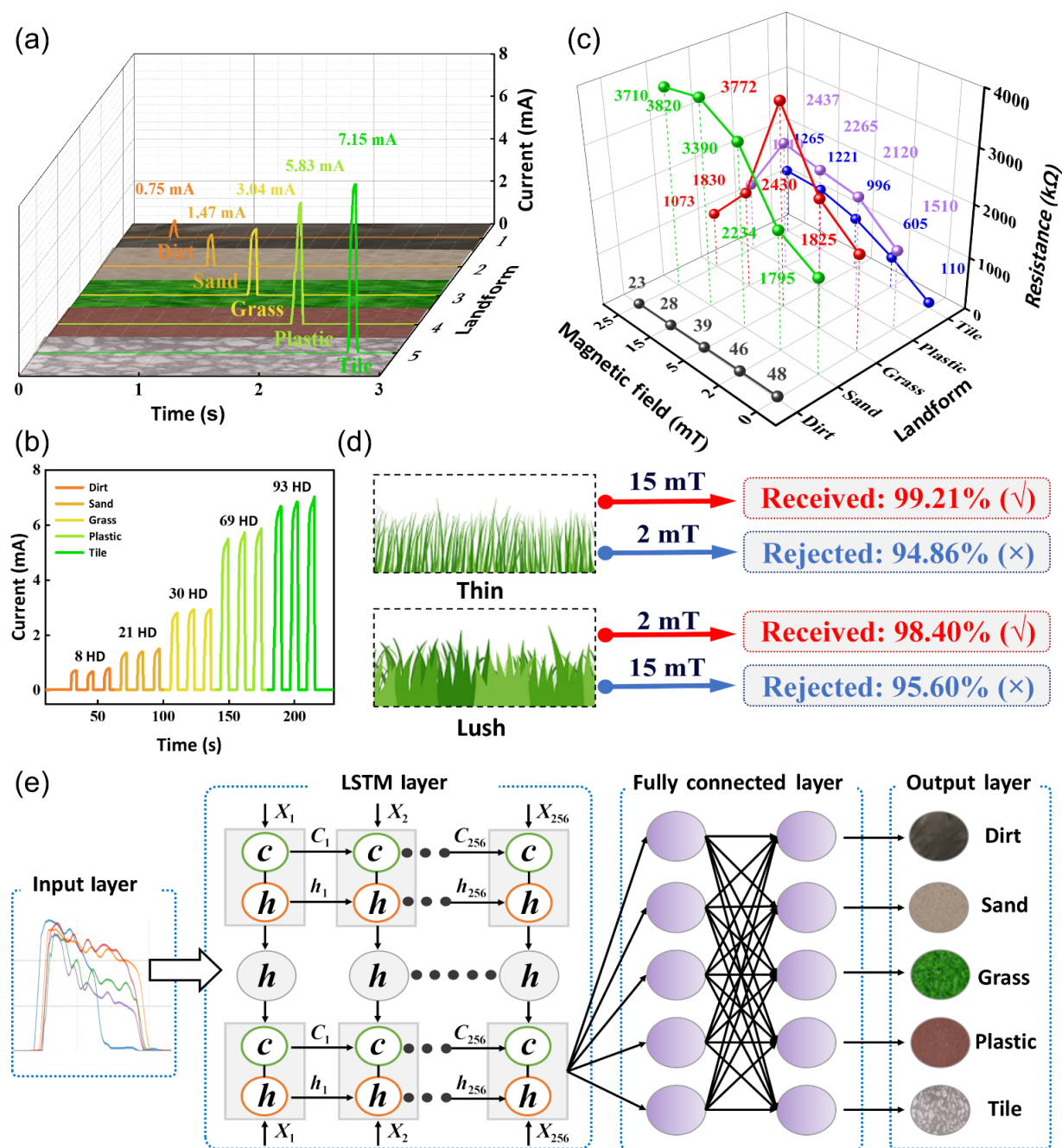


Figure 5 Application validation of the electronic skin for ground environment recognition. ((a) and (b)) Current response curves of the device and dynamic response during unloading cycles when the CyberDog steps on different ground surfaces under no magnetic field. (c) Variation in the peak response resistance of the device when the CyberDog steps on different ground surfaces under varying magnetic fields. (d) Comparison of the device's recognition rates when the CyberDog walks on dense and sparse lawns. (e) Architecture diagram of the neural network for ground recognition.

information on system latency. In summary, this study successfully developed an adaptive recognition e-skin system with dynamic environmental perception through multi-scenario experimental validation.

4 Conclusions

In summary, we successfully fabricated a flexible and adaptive bionic e-skin. By exploring the integration of novel smart materials with ingenious micro-nano structures and utilizing the piezoresistive sensing mechanism, multi-objective optimization is

achieved through magnetic fields. Consequently, the device delivers optimal signal response under corresponding magnetic field strengths across varying pressure environments, significantly expanding its application prospects in fields such as robotic tactile intelligent interaction. At low pressures and small magnetic fields, the sensor exhibits high sensitivity (235.6 kPa^{-1}) and high resolution (1/1000), enabling precise capture of minute tactile information. At medium pressure and magnetic field levels, the sensor maintains high resolution (1/1250) and high signal-to-noise ratio (89 dB), making it suitable for diverse practical applications. At high pressure and strong magnetic fields, the sensor offers an expanded

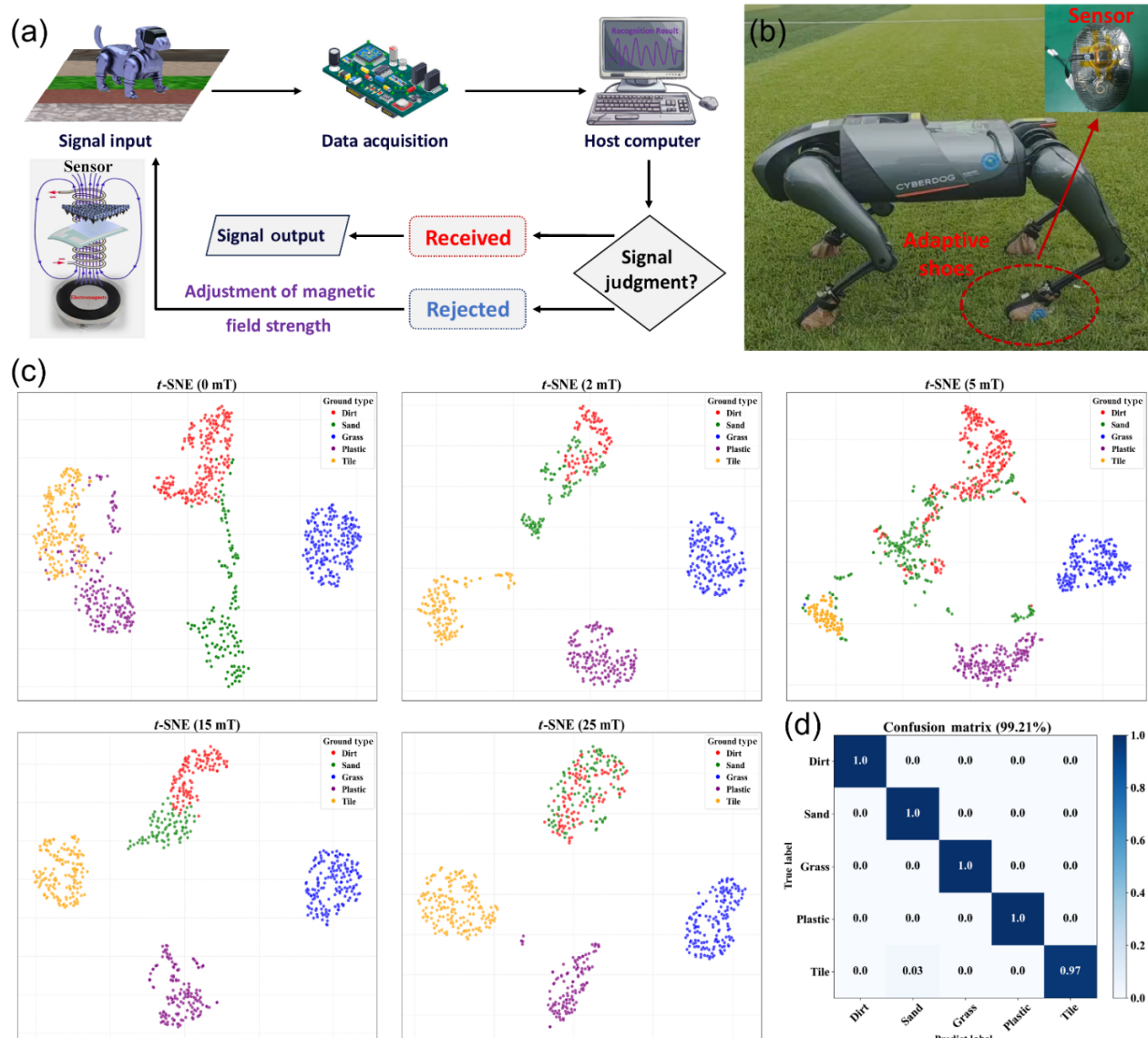


Figure 6 Adaptive recognition e-skin system for ground environment. (a) Block diagram illustrating the logic flow of the adaptive recognition process. (b) Demonstration of the CyberDog wearing adaptive shoes on an outdoor lawn. (c) *t*-SNE results of sensor recognition for different terrains under varying magnetic fields. (d) Confusion matrix diagram depicting the recognition accuracy of the device.

measurement range (0–3.5 MPa), enabling it to withstand intense tactile stimuli in complex environments. Additionally, this device features fast recovery time (10 ms), excellent stability (> 10,000 cycles), and stable dynamic response. These characteristics enable the e-skin to adaptively recognize diverse terrain environments and distinguish subtle variations within the same terrain when applied to the footpad of a robotic dog, achieving an optimal accuracy rate of 99.21%. Such tactile adaptive devices not only enhance the accuracy of information acquisition for robots in complex environments but also adjust performance parameters in response to external changes to maintain optimal sensing performance. In addition, the sensor response under multi-axial complex loads has not been systematically investigated in this study. In future work, we will conduct systematic multi-dimensional force loading experiments to achieve adaptive sensing with decoupling of multi-dimensional forces, such as normal and tangential forces.

Electronic Supplementary Material: Supplementary material (characterization of materials, test data of device performance, further details of PCB circuit, photo of adaptive function shoes, and other experimental figures) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908965>.

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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 62471454), the Project of Chongqing Science and Technology Bureau (Nos. CSTB2024TIAD-KPX0040,

CSTB2025TIAD-KPX0097, and CSTB2023TIAD-STX0037), the National Natural Science Foundation of China (Nos. 22479101 and 22209118), Shenzhen Science and Technology Program (No. KJZD20240903100700001), the Project of Chongqing Economic and Information Commission (No. YJX-2025001001007), and Natural Science Foundation of Sichuan (No. 2024NSFSC0233).

Declaration of competing interest

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

Author contribution statement

D. P. W. conceived and designed the experiments. D. P. W. supervised the project. B. X. Z. performed the experiments, including device fabrication and characterization. D. W. and T. T. provided method of material preparation. X. L. G. and G. Y. C. helped with the measurements of the materials. X. L. G. designed the haptic algorithm. B. X. Z., J. X., and C. F. Z. analyzed the experimental data. B. X. Z. wrote the manuscript. W. Z., H. N. L., and D. P. W. reviewed and finalized the manuscript. All the authors have approved the final manuscript.

Use of AI statement

During the preparation of this work, the authors used ChatGPT in order to polish the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- [1] Hammock, M. L.; Chortos, A.; Tee, B. C. K.; Tok, J. B. H.; Bao, Z. A. 25th anniversary article: The evolution of electronic skin (e-skin): A brief history, design considerations, and recent progress. *Adv. Mater.* **2013**, *25*, 5997–6038.
- [2] Tan, C. X.; Dong, Z. G.; Li, Y. H.; Zhao, H. G.; Huang, X. Y.; Zhou, Z. C.; Jiang, J. W.; Long, Y. Z.; Jiang, P. K.; Zhang, T. Y. et al. A high performance wearable strain sensor with advanced thermal management for motion monitoring. *Nat. Commun.* **2020**, *11*, 3530.
- [3] Ershad, F.; Thukral, A.; Yue, J. P.; Comeaux, P.; Lu, Y. T.; Shim, H.; Sim, K.; Kim, N. I.; Rao, Z.; Guevara, R. et al. Ultra-conformal drawn-on-skin electronics for multifunctional motion artifact-free sensing and point-of-care treatment. *Nat. Commun.* **2020**, *11*, 3823.
- [4] Han, L.; Lu, X.; Wang, M. H.; Gan, D. L.; Deng, W. L.; Wang, K. F.; Fang, L. M.; Liu, K. Z.; Chan, C. W.; Tang, Y. H. et al. A mussel-inspired conductive, self-adhesive, and self-healable tough hydrogel as cell stimulators and implantable bioelectronics. *Small* **2017**, *13*, 1601916.
- [5] Mahato, B.; Kaya, K. D.; Fan, Y.; Sumien, N.; Shetty, R. A.; Zhang, W.; Davis, D.; Mock, T.; Batabyal, S.; Ni, A. G. et al. Pharmacologic fibroblast reprogramming into photoreceptors restores vision. *Nature* **2020**, *581*, 83–88.
- [6] Robinson, J. T.; Pohlmeier, E.; Gather, M. C.; Kemere, C.; Kitching, J. E.; Malliaras, G. G.; Marblestone, A.; Shepard, K. L.; Stieglitz, T.; Xie, C. Developing next-generation brain sensing technologies—A review. *IEEE Sens. J.* **2019**, *29*, 10163–10175.
- [7] Kim, J.; Campbell, A. S.; de Ávila, B. E. F.; Wang, J. Wearable biosensors for healthcare monitoring. *Nat. Biotechnol.* **2019**, *37*, 389–406.
- [8] Iqbal, S. M. A.; Mahgoub, I.; Du, E.; Leavitt, M. A.; Asghar, W. Advances in healthcare wearable devices. *npj Flex. Electron.* **2021**, *5*, 9.
- [9] Kwon, Y. T.; Kim, Y. S.; Kwon, S.; Mahmood, M.; Lim, H. R.; Park, S. W.; Kang, S. O.; Choi, J. J.; Herbert, R.; Jang, Y. C. et al. All-printed nanomembrane wireless bioelectronics using a biocompatible solderable graphene for multimodal human-machine interfaces. *Nat. Commun.* **2020**, *11*, 3450.
- [10] Mishra, S.; Kim, Y. S.; Intarasirisawat, J.; Kwon, Y. T.; Lee, Y.; Mahmood, M.; Lim, H. R.; Herbert, R.; Yu, K. J.; Ang, C. S. et al. Soft, wireless periocular wearable electronics for real-time detection of eye vergence in a virtual reality toward mobile eye therapies. *Sci. Adv.* **2020**, *6*, eaay1729.
- [11] Low, Z. W. K.; Li, Z. B.; Ow, C.; Chee, P. L.; Ye, E. Y.; Kai, D.; Yang, D. P.; Loh, X. J. Using artificial skin devices as skin replacements: Insights into superficial treatment. *Small* **2019**, *15*, 1805453.
- [12] Ma, Y. J.; Zhang, Y. C.; Cai, S. S.; Han, Z. Y.; Liu, X.; Wang, F. L.; Cao, Y.; Wang, Z. H.; Li, H. F.; Chen, Y. H. et al. Flexible hybrid electronics for digital healthcare. *Adv. Mater.* **2020**, *32*, 1902062.
- [13] Ling, Y. Z.; An, T. C.; Yap, L. W.; Zhu, B. W.; Gong, S.; Cheng, W. L. Disruptive, soft, wearable sensors. *Adv. Mater.* **2020**, *32*, 1904664.
- [14] Xu, K. C.; Lu, Y. Y.; Takei, K. Flexible hybrid sensor systems with feedback functions. *Adv. Funct. Mater.* **2021**, *31*, 2007436.
- [15] Tian, G.; Guo, L.; Gao, Y. Y.; Deng, W. L.; Wang, S. L.; Xu, T. P.; Peng, L.; Zhang, B. B.; Yang, T.; Lan, B. L. et al. A wearable all-in-one obstructive sleep apnea management system with flexible piezoelectric monitoring and soft magnetoelastic stimulating. *Matter* **2025**, *8*, 102323.
- [16] Yuan, Z. H.; Wang, T.; Shao, C. Y.; Yang, S. R.; Sun, W. X.; Chen, Y. H.; Peng, Z. P.; Tong, Z. Bioinspired green underwater adhesive gelatin-tannic acid hydrogel with wide range adjustable adhesion strength and multiple environmental adaptability. *Adv. Funct. Mater.* **2025**, *35*, 2412950.
- [17] Yan, Y. Y.; Zheng, J. Z.; Zhang, Q. R.; Li, Y. L.; Li, G. F.; Zhang, Z. K.; Wang, P.; Wu, W. J.; Zhai, J. Y.; Xu, Y. Ultrafast piezoresistive flexible pressure sensor for vibration and sound detection with a bandwidth over 20 kHz. *Chem. Eng. J.* **2025**, *517*, 164221.
- [18] Xian, S.; Xu, Y.; Li, Y. X.; Wu, Z. F.; Xie, X.; Wu, Z. G.; Yang, X. Y.; Zhong, Y. Flexible triboelectric sensor based on catalyst-diffusion self-encapsulated conductive liquid-metal-silicone ink for somatosensory soft robotic system. *Adv. Funct. Mater.* **2025**, *35*, 2412293.
- [19] Chou, H. H.; Nguyen, A.; Chortos, A.; To, J. W. F.; Lu, C. E.; Mei, J. G.; Kurosawa, T.; Bae, W. G.; Tok, J. B. H.; Bao, Z. N. A chameleon-inspired stretchable electronic skin with interactive colour changing controlled by tactile sensing. *Nat. Commun.* **2015**, *6*, 8011.
- [20] Rao, Z.; Ershad, F.; Almasri, A.; Gonzalez, L.; Wu, X. Y.; Yu, C. J. Soft electronics for the skin: From health monitors to human-machine interfaces. *Adv. Mater. Technol.* **2020**, *5*, 2000233.
- [21] Wang, Z. W.; Guo, S. J.; Li, H. W.; Wang, B.; Sun, Y. T.; Xu, Z. Y.; Chen, X. S.; Wu, K. J.; Zhang, X. T.; Xing, F. F. et al. The semiconductor/conductor interface piezoresistive effect in an organic transistor for highly sensitive pressure sensors. *Adv. Mater.* **2019**, *31*, 1805630.
- [22] Zang, Y. P.; Zhang, F. J.; Huang, D. Z.; Gao, X. K.; Di, C. A.; Zhu, D. B. Flexible suspended gate organic thin-film transistors for ultra-sensitive pressure detection. *Nat. Commun.* **2015**, *6*, 6269.
- [23] Cao, Y.; Tan, Y. J.; Li, S.; Lee, W. W.; Guo, H. C.; Cai, Y. Q.; Wang, C.; Tee, B. C. K. Self-healing electronic skins for aquatic environments. *Nat. Electron.* **2019**, *2*, 75–82.
- [24] Lee, D.; Lee, H.; Jeong, Y.; Ahn, Y.; Nam, G.; Lee, Y. Highly sensitive, transparent, and durable pressure sensors based on sea-urchin shaped metal nanoparticles. *Adv. Mater.* **2016**, *28*, 9364–9369.
- [25] Kim, J. O.; Kwon, S. Y.; Kim, Y.; Choi, H. B.; Yang, J. C.; Oh, J.; Lee, H. S.; Sim, J. Y.; Ryu, S.; Park, S. Highly ordered 3D microstructure-based electronic skin capable of differentiating pressure, temperature, and proximity. *ACS Appl. Mater. Interfaces* **2019**, *11*, 1503–1511.
- [26] Bica, I.; Anitas, E. M. Light transmission, magnetodielectric and

- magnetoresistive effects in membranes based on hybrid magnetorheological suspensions in a static magnetic field superimposed on a low/medium frequency electric field. *J. Magn. Magn. Mater.* **2020**, *511*, 166975.
- [27] Zhuo, S. Y.; Song, C.; Rong, Q. F.; Zhao, T. Y.; Liu, M. J. Shape and stiffness memory ionogels with programmable pressure-resistance response. *Nat. Commun.* **2022**, *13*, 1743.
- [28] Lin, W. E.; Wang, Z. Y.; Xu, Y. T.; Hu, Z. X.; Zhao, W. Y.; Zhu, Z. H.; Sun, Z. L.; Wang, G. X.; Peng, Z. C. Self-adaptive perception of object's deformability with multiple deformation attributes utilizing biomimetic mechanoreceptors. *Adv. Mater.* **2024**, *36*, 2305032.
- [29] Shao, L.; Xu, X. Z.; Liu, Y. Q.; Zhao, Y. Adaptive memory of a neuromorphic transistor with multi-sensory signal fusion. *ACS Appl. Mater. Interfaces* **2023**, *15*, 35272–35279.
- [30] Ramachandran, H.; Mu, E. W.; Lomeli, E. G.; Braun, A.; Goto, M.; Hsu, K. H.; Liu, J.; Jiang, Z. L.; Lim, K.; Busse, G. M. et al. A formal FeIII/V redox couple in an intercalation electrode. *Nat. Mater.* **2026**, *25*, 91–99.
- [31] Tan, P.; Wang, H. F.; Xiao, F. R.; Lu, X.; Shang, W. H.; Deng, X. B.; Song, H. F.; Xu, Z. Y.; Cao, J. F.; Gan, T. S. et al. Solution-processable, soft, self-adhesive, and conductive polymer composites for soft electronics. *Nat. Commun.* **2022**, *13*, 358.
- [32] Kim, A.; Kim, C.; Waltmann, T.; Vo, T.; Kim, E. M.; Kim, J.; Shao, Y. T.; Michelson, A.; Crockett, J. R.; Kalutanirige, F. C. et al. Patchy nanoparticles by atomic stencilling. *Nature* **2025**, *646*, 592–600.
- [33] Choong, C. L.; Shim, M. B.; Lee, B. S.; Jeon, S.; Ko, D. S.; Kang, T. H.; Bae, J.; Lee, S. H.; Byun, K. E.; Im, J. et al. Highly stretchable resistive pressure sensors using a conductive elastomeric composite on a micropillar array. *Adv. Mater.* **2014**, *26*, 3451–3458.
- [34] Zhang, H.; Chen, H. M.; Lee, J. H.; Kim, E. Y.; Chan, K.; Venkatesan, H.; Shen, X.; Yang, J. L.; Kim, J. K. Mechanochromic optical/electrical skin for ultrasensitive dual-signal sensing. *ACS Nano* **2023**, *17* (6), 5921–5934.
- [35] Cho, S. H.; Lee, S. W.; Yu, S.; Kim, H.; Chang, S.; Kang, D.; Hwang, I.; Kang, H. S.; Jeong, B.; Kim, E. H. et al. Micropatterned pyramidal ionic gels for sensing broad-range pressures with high sensitivity. *ACS Appl. Mater. Interfaces* **2017**, *9*, 10128–10135.
- [36] Yun, G. L.; Tang, S. Y.; Sun, S. S.; Yuan, D.; Zhao, Q. B.; Deng, L.; Yan, S.; Du, H. P.; Dickey, M. D.; Li, W. H. Liquid metal-filled magnetorheological elastomer with positive piezoelectricity. *Nat. Commun.* **2019**, *10*, 1300.
- [37] Cooper, C. B.; Root, S. E.; Michalek, L.; Wu, S.; Lai, J. C.; Khatib, M.; Oyakhire, S. T.; Zhao, R.; Qin, J.; Bao, Z. N. Autonomous alignment and healing in multilayer soft electronics using immiscible dynamic polymers. *Science* **2023**, *380*, 935–941.
- [38] Ding, L.; Wang, Y.; Sun, C. L.; Shu, Q.; Hu, T.; Xuan, S. H.; Gong, X. L. Three-dimensional structured dual-mode flexible sensors for highly sensitive tactile perception and noncontact sensing. *ACS Appl. Mater. Interfaces* **2020**, *12*, 20955–20964.
- [39] Cao, X. F.; Xuan, S. H.; Gao, Y. D.; Lou, C. C.; Deng, H. X.; Gong, X. L. 3D printing ultraflexible magnetic actuators via screw extrusion method. *Adv. Mater.* **2022**, *9*, 2200898.
- [40] Qi, S.; Guo, H. Y.; Fu, J.; Xie, Y. P.; Zhu, M.; Yu, M. 3D printed shape-programmable magneto-active soft matter for biomimetic applications. *Compos. Sci. Technol.* **2020**, *188*, 107973.
- [41] He, X. C.; Cui, Z. Q.; Zhang, F. L.; Li, Y. Z.; Tu, J. Q.; Cao, J. W.; Wang, J. W.; Qiao, Y. C.; Xi, P. X.; Xu, T. L. et al. Multiscale heterogeneities-based piezoresistive interfaces with ultralow detection limitation and adaptively switchable pressure detectability. *ACS Nano* **2024**, *18*, 8296–8306.
- [42] Vaghef-Koodehi, A. *Graphene-Enhanced Robotic Touch Sensors with Tunable Sensitivity for Advanced Automation Applications* [Online]. https://preprints.opticaopen.org/articles/preprint/Graphene-Enhanced_Robotic_Touch_Sensors_with_Tunable_Sensitivity_for_Advanced_Automation_Applications/29230877/1?file=55094852 (accessed Mar 10, 2026).
- [43] Jenkinson, G. P.; Conn, A. T.; Tzemanaki, A. ESPRESSO: Eustachian tube-inspired tactile sensor exploiting pneumatics for range extension and Sensitivity tuning. *Sensors* **2023**, *23*, 567.
- [44] Guo, H. Y.; Liu, J. X.; Liu, H. Y.; Yang, M.; Zhao, J. W.; Lu, T. Q. Iontronic dynamic sensor with broad bandwidth and flat frequency response using controlled preloading strategy. *ACS Nano* **2024**, *18*, 5599–5608.
- [45] Park, Y. J.; Choi, S. B. Sensors and sensing devices utilizing electrorheological fluids and magnetorheological materials—A review. *Sensors* **2024**, *24*, 2842.
- [46] Halsey, T. C. Electrorheological fluids. *Science* **1992**, *258*, 761–766.
- [47] Yoon, C. M.; Jang, Y.; Noh, J.; Kim, J.; Jang, J. Smart fluid system dually responsive to light and electric fields: An electrophotoreological fluid. *ACS Nano* **2017**, *11*, 9789–9801.
- [48] Xu, Y. G.; Gong, X. L.; Wan, Q.; Liu, T. X.; Xuan, S. H. Magneto-sensitive smart soft material and magnetorheological mechanism. *Adv. Mech.* **2015**, *45*, 201508.
- [49] Guerrero-Sanchez, C.; Lara-Ceniceros, T.; Jimenez-Regalado, E.; Raşa, M.; Schubert, U. S. Magnetorheological fluids based on ionic liquids. *Adv. Mater.* **2007**, *19*, 1740–1747.
- [50] Feng, Y.; Verboncoeur, J. P. A model for effective field enhancement for Fowler–Nordheim field emission. *Phys. Plasmas* **2005**, *12*, 103301.
- [51] Ralph Howard Fowler, F. R. S.; Nordheim, L. Electron emission in intense electric fields. *Proc. Roy. Soc. A: Math., Phys. Eng. Sci.* **1928**, *119*, 173–181.
- [52] Wang, Y.; Xuan, S. H.; Dong, B.; Xu, F.; Gong, X. L. Stimuli dependent impedance of conductive magnetorheological elastomers. *Smart Mater. Struct.* **2016**, *25*, 025003.
- [53] Shen, Z. Q.; Zhu, X. Y.; Majidi, C.; Gu, G. Y. Cutaneous ionogel mechanoreceptors for soft machines, physiological sensing, and amputee prostheses. *Adv. Mater.* **2021**, *33*, 2102069.
- [54] Kwon, S. Y.; Park, G.; Jin, H.; Gu, C.; Oh, S. J.; Sim, J. Y.; Youm, W.; Kim, T. S.; Kim, H. J.; Park, S. On-skin and tele-haptic application of mechanically decoupled tactile array on dynamically moving and soft surfaces. *npj Flex. Electron.* **2022**, *6*, 98.
- [55] Crozier, P. A.; Leibovich, M.; Haluai, P.; Tan, M.; Thomas, A. M.; Vincent, J.; Mohan, S.; Morales, A. M.; Kulkarni, S. A.; Matteson, D. S. et al. Visualizing nanoparticle surface dynamics and instabilities enabled by deep denoising. *Science* **2025**, *387*, 949–954.



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