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Flexible Tactile Sensors for Enhancing Robotic Perception

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Abstract: As robotic technology advances towards autonomy and intelligence, tactile sensing systems have become a key technology for overcoming the bottleneck of environmental interaction. Unlike visual perception, which captures macroscopic information, tactile sensing provides precise mechanical feedback for robotic manipulation by real-time analysis of microscopic physical parameters such as contact force, material properties, and surface morphology. This is particularly important in application scenarios that require high precision in force control, such as minimally invasive surgery and precision assembly, where the sensitivity, multimodal perception capabilities, and environmental adaptability of tactile sensors directly determine the operational performance of the robotic system. However, traditional tactile sensors are limited by rigid structures, limited sensitivity, and a single perception modality, making it difficult to meet the demands of complex interactions. In recent years, breakthroughs in flexible electronic materials, biomimetic microstructure design, and multimodal sensing integration technologies have provided innovative opportunities for tactile sensing systems. This review provides a detailed overview of the key technological advancements in tactile sensors and their applications in robotic surfaces, analyzes the major challenges currently faced, and looks ahead to future development directions, particularly the potential in flexible materials and intelligent algorithms.

Keywords: tactile sensor, robot, pressure sensor, multifunctional sensing

1. Introduction

With the rapid development of robotic technology and automation systems, the demands for perception capabilities in robots for precise operation and complex task execution are continuously increasing [1–4].

As a core component of robotic perception systems, tactile sensing technology plays a crucial role in enhancing the autonomy, flexibility, and adaptability of robots in handling complex tasks [5–8]. By simulating human tactile functions, tactile sensors can not only be used for human health monitoring and motion detection but also have widespread applications in robotic surfaces for tactile perception, helping robots more accurately sense and respond to environmental information. This, in turn, greatly improves the intelligence level and work efficiency of robots in industries such as manufacturing, healthcare, and services [9–13].

However, existing traditional tactile sensor technologies still face many challenges. For example, many traditional sensors, due to their rigid structures, struggle to adapt to complex flexible surfaces, leading to inaccurate force feedback [14, 15]. Moreover, there are significant differences in their ability to perceive various types of forces (such as normal force, shear force, and bending force), which limits their accuracy in multimodal applications [16–18]. Additionally, the limitations in sensitivity [19, 20] response speed [21, 22] and adaptability of traditional sensors restrict their potential for high-precision task [23, 24]. To overcome these limitations, significant progress has been made in the research of flexible materials and intelligent tactile sensors. In recent years, the emergence of new sensor materials such as ion-electronic sensors [25, 26] hydrogel sensors [27–29], and flexible electronic skins has greatly improved the sensitivity, response speed, and environmental adaptability of tactile sensors [30–33]. In particular, in the medical field, these innovative technologies enable robots to accurately perceive small changes in tissue hardness, providing more precise force feedback during surgery and preventing damage to surrounding tissues [34, 35]. In industrial automation, tactile sensors allow robots to achieve high-precision force control in precision assembly and manufacturing,

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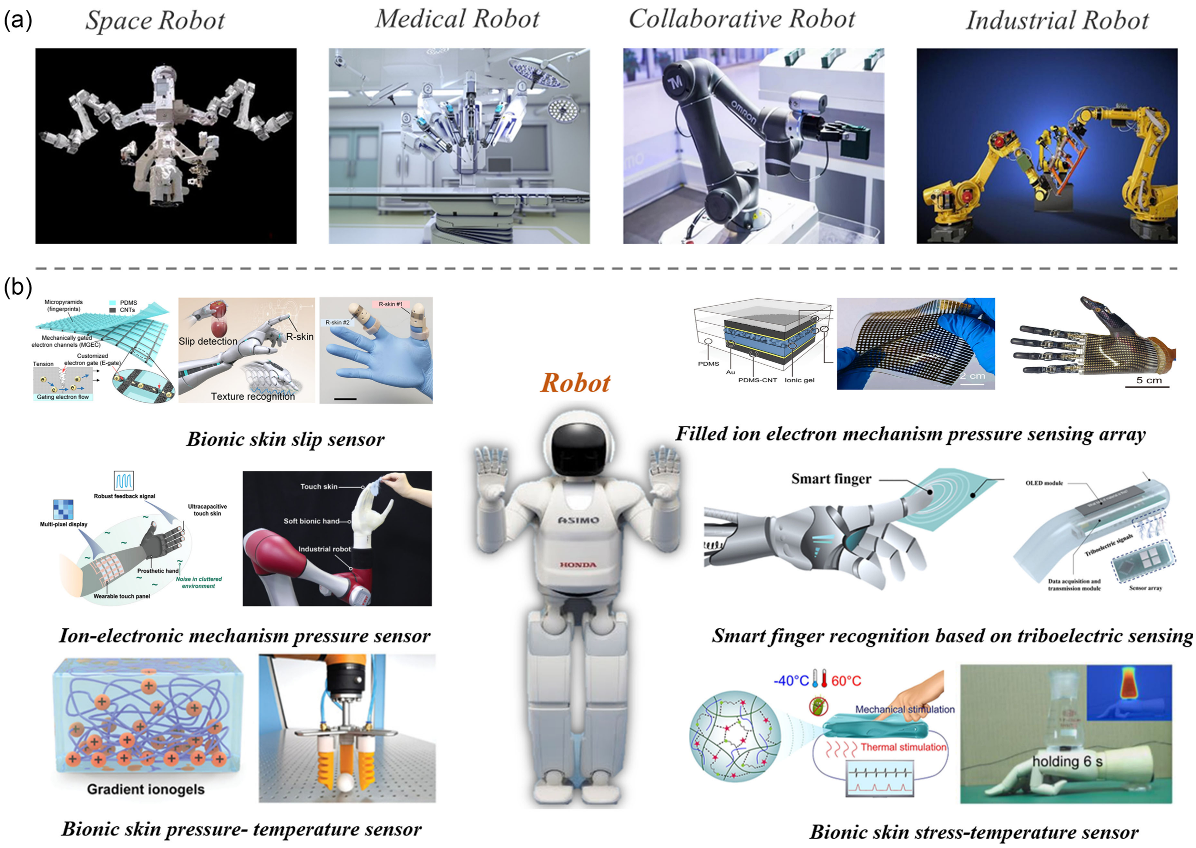
Figure 1
The tactile sensor is applied to human body as health or motion monitoring and to robot tactile sense



thereby improving production efficiency and product quality [36, 37] (Figure 1).

Nevertheless, existing tactile sensor technologies still face many pressing challenges, especially in areas such as sensor sensitivity, multimodal force perception fusion, and system integration [38–41]. Therefore, further research on tactile sensing systems remains a key area of robotic technology development. In the future, with the continuous advancement of flexible materials, sensing mechanisms, and intelligent algorithms, tactile sensors are expected to achieve even greater breakthroughs in precise sensing, flexible applications, and strong adaptability. This review will review the latest developments in tactile sensor technology, particularly sensor designs based on novel materials and structural optimization, analyze their application results and challenges in robotic perception systems, and provide a theoretical foundation and technical direction for the future research and development of tactile sensing technology through a systematic analysis of existing technologies.

2. Pressure Sensing Mechanism and Structural Design

Pressure sensors, as a key research focus in the field of tactile sensing, have developed a variety of technological solutions, including resistive, capacitive, and triboelectric types [42–45]. Tactile sensors can convert externally applied pressure into electrical signals, and by analyzing the changes in these signals, they can determine the magnitude and/or direction of the pressure. Each conversion mechanism has unique characteristics depending on the materials and structures used [46–48]. Next, we will provide a brief overview of the basic structure, common materials, and operating principles of these sensors.

2.1. Resistive tactile sensors

Resistive tactile sensors operate based on the principle of resistance change caused by pressure. When external pressure is applied to the sensor, the contact area between the conductive material in the electrodes increases, leading to a decrease in resistance [44, 49, 50]. Common conductive materials include carbon nanotubes [51–53] and silver nanowires [54, 55], while flexible materials such as PDMS [56, 57] or fibers [47, 58, 59] are typically used as substrates. Jia et al. [60] used MXene nanosheets with accordion-like nanostructures and protruding structures transferred from sandpaper, detecting resistance changes based on the interlayer contact area variation during the pressure loading process. Resistive sensors offer good cost-effectiveness and are suitable for simple tactile sensing, but they have limitations in terms of high precision and fast response [61].

2.2. Capacitive tactile sensors

Capacitive tactile sensors detect external pressure by causing changes in the geometric structure of the electrodes, which in turn affects the capacitance value, establishing a relationship between pressure and capacitance [62–64]. Common electrode materials include metallic nanowires [65–67] and graphene [68–70], while dielectric layers are typically made from flexible materials such as PDMS and polyurethane [71–73]. Lv et al. [74] developed an

MWCNT/PDMS dielectric layer with spontaneous wrinkling characteristics, exhibiting ultra-high linearity in capacitive sensing, making it capable of detecting weak signals and successfully integrating it into the surface of pneumatic fingers for hardness sensing. Luo et al. [75] fabricated a capacitive sensor with a dielectric layer of inclined micro-pillar arrays, utilizing the reduction of air gaps during pressure loading to increase capacitance, and its simple, easy-to-manufacture structure makes it highly suitable for wearable technologies. Capacitive sensors offer high sensitivity and precision, making them widely used for precise tactile sensing and surface texture recognition.

2.3. Piezoelectric tactile sensors

Piezoelectric tactile sensors work by generating a voltage change in piezoelectric materials when subjected to external force [76–79]. Common piezoelectric materials include polyvinylidene fluoride (PVDF) [80–82] and lead zirconate titanate [83, 84]. External pressure induces deformation in the material, causing a change in the dipole density, which generates a voltage signal. These sensors offer sensitive dynamic responses, making them suitable for vibration detection and texture recognition, but they tend to perform poorly in static pressure sensing. Seong et al. [77] developed $BaTiO_3$/PDMS materials by combining piezoelectric materials with micro-patterning techniques, exhibiting high sensitivity and a wide pressure range. Huang et al. [85] prepared PVDF/BTO composites and used a porous structure as a pressure sensor, with a high output of approximately 20.0 V and a sensitivity of ~132.87 mV/kPa, demonstrating long-term durability. PVDF-based sensors are widely applied in practical scenarios due to their flexibility, low cost, and ease of processing.

2.4. Triboelectric tactile sensors

Triboelectric tactile sensors detect changes in voltage generated by the contact and separation of materials with different electronegativities. The triboelectric nanogenerators (TENG) senses pressure through the combination of triboelectric and electrostatic effects [86, 87]. Its output signal is closely related to changes in the contact area and pressure frequency. Triboelectric sensors exhibit strong dynamic pressure sensing capabilities, making them suitable for wearable devices and flexible sensors. Common materials used include PDMS and PTFE [88–90]. Pradhan et al. [91] developed self-sustaining smart footwear featuring 3D-printed TPU spring-based EMG/TENG for pressure sensing/power and laser-induced graphene (LIG) temperature sensors, enabling wireless diabetic foot ulcer monitoring. Wang et al. [92] fabricated a PAM/$BaTiO_3$ composite film that is flexible, stretchable, and highly transparent, achieving high sensitivity to pressure via the triboelectric effect (Figure 2 [53, 61, 74, 75, 77, 85]).

An analysis of the working principles of tactile sensors reveals that the material requirements vary depending on the sensor type.

Figure 2

Example of sensors with four different mechanisms: (a) changes in MWCNT/quartz fabric structure before and after pressure loading, (b) structural and circuit changes of MXene/PDMS structure under different pressure loading, (c) structural and circuit changes of MWCNT/PDMS layer during pressure loading, (d) pressure sensing process of microcolumn structure, (e) mechanism of $BaTiO_3$/PDMS pyramid structure under pressure loading, and (f) changes in loading and unloading process of PVDF/BTO composite

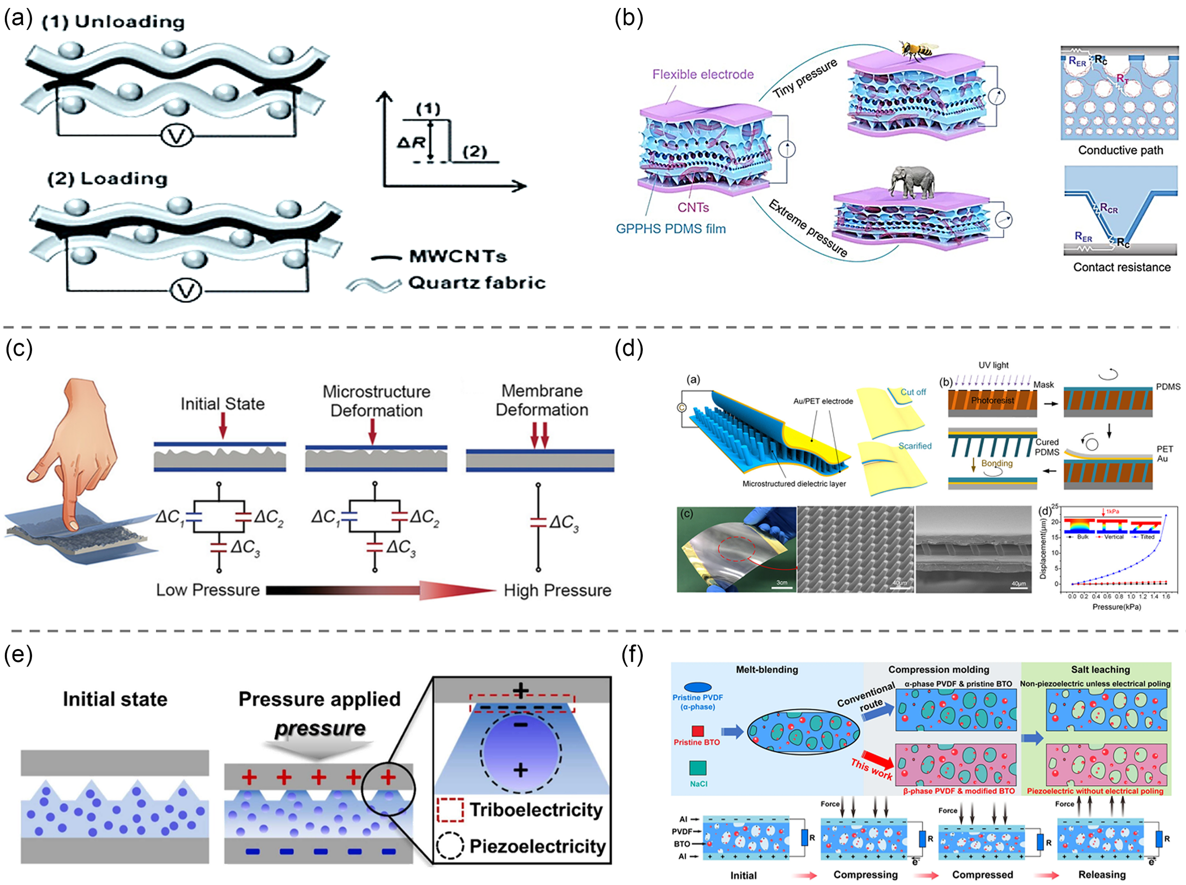


Table 1
Sensitivity and performance comparison of different types of sensors

Sensor type	Sensitivity (kPa^{-1})	Materials used	Range (KPa)	Response time	Reference
Resistive	0.127	CNTs@HAPAAm	0–50	600 ms	[53]
Resistive	4.97	rGO@CNTs/CS	0–3	170 ms	[52]
Capacitive	0.33	PDMS@Graphene	0–5	20 ms	[68]
Capacitive	2.04	PDMS@AgNWs	0–8	100 ms	[66]
Piezoelectric	0.0393	P(VDF-TrFE) @BN	–	30 ms	[76]
Piezoelectric	4.19	$BaTiO_3$@PDMS	0–100	–	[77]
Triboelectric	0.75	$BaTiO_3$@PDMS@AgNWs	0–140	–	[87]
Triboelectric	–	EGaIn@PDMS	0–100	–	[89]
Ion-electronic	3302	PVA@H_3PO_4	0–400	9 ms	[93]
Ion-electronic	1716	PAM@Alg@Zn^{2+}	0–200	30 ms	[94]

Resistive and capacitive sensors depend on the conductivity and dielectric layer properties, with common materials including nanometer-scale conductive substances (e.g., carbon nanotubes, silver nanowires, graphene) and highly elastic and flexible matrix materials (e.g., PDMS). Piezoelectric and triboelectric sensors, on the other hand, rely primarily on the material's stress and charge response mechanisms. PVDF, due to its good flexibility and low production cost, is a popular choice for piezoelectric sensors. Triboelectric sensors achieve efficient energy conversion and pressure sensing through composite materials with different electronegativities. Typically, representative sensitivity pairs of different mechanisms are shown in Table 1. Representative structural and material comparisons of haptic sensors of different mechanisms from 2010 to 2025 are shown in Table 2. PDMS-based materials (with CNTs, silver nanowire (AgNWs), MXene) are commonly used for flexible, stretchable sensors due to PDMS's inherent flexibility and the conductive fillers enhancing its performance. These materials offer a balance of mechanical flexibility and electrical conductivity. PU and fiber-based materials provide high mechanical flexibility and can be used in textile-based sensors. Their properties can be further optimized by adding conductive fillers such as CNTs and AgNWs. PVA and PAM-based composites show high sensitivity, with PVA/MXene being particularly noted for its impressive sensitivity, making it useful in highly responsive sensor applications. Materials like PDMS, PU, Fiber, PVA, and PAM, when combined with conductive fillers like CNTs, AgNWs, and MXene, can be engineered to provide sensors with varying sensitivities, flexibility, and mechanical properties. Examples of different materials are shown in Table 3. In addition, some commercial sensors are listed as shown in Table 4.

2.5. The development of ion-electronic sensors

Although capacitive sensors have a simple structure and high stability, their ability to achieve high sensitivity over a wide range is limited when relying solely on changes in sensor thickness. In 2012, Nie et al. [151] proposed an innovative sensor structure using ion-containing droplets as the medium between electrodes.

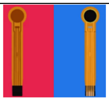
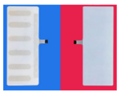
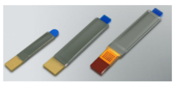
Table 2
Technology evolution in tactile sensors (2010–2025)

Year	Sensing Type	Structure	Materials	References
2010–2014	Resistance	Hollow-Sphere	PPy	[95]
	Resistance	Copper Mesh	Graphene/PDMS	[96]
	Capacitance	Air Gap	PDMS/SWNT	[97]
	Capacitance	Hydrophobic Sponge	PDMS/Al	[98]
	Piezoelectric	–	Zirconate Titanate	[99]
	Piezoelectric	Dome	PDMS	[100]
	Triboelectric	Nanorod (NR) arrays	FEP	[101]
	Triboelectric	Etched Nanowire	PA/PTFE	[102]
2015–2020	Resistance	Pyramid	PDMS/AgNWs	[103]
	Resistance	Porous	PAA/CNT	[104]
	Capacitance	Micro-pillar Arrays	Au/PET	[75]
	Capacitance	Pyramidal Microstructures	ITO/PET/PDMS	[105]
	Piezoelectric	–	PTNWs/Graphene	[78]
	Piezoelectric	–	AlGaN/GaN	[106]
	Triboelectric	Micro/Nanostructure	PDMS/EVA	[22]
	Triboelectric	Interlocking	PDMS/PTFE/AgNWs	[107]
2021–2025	Resistance	Spider Web-Like	PIFs/CNT	[108]
	Resistance	Multi-level nano-Microstructures	PDMS/MXene	[60]
	Capacitance	Micro-cilia array Micro-dome array	CNT/PDMS	[19]
	Capacitance	Graded intrafillable	PVA/H_3PO_4	[93]
	Piezoelectric	–	Fibers/CNT	[109]
	Piezoelectric	Micropyramidal	$BaTiO_3$/PDMS	[77]
	Triboelectric	Cellulosic	CNTs/ Cellulosic	[110]
	Triboelectric	LiCl/ CNTs	Ion gradient	[43]

Table 3
Comparison of common flexible sensor materials and their sensitivities

Base material (Conductive)	Materials	Sensitivity	References
PDMS (CNTs AgNWs MXene)	PDMS/CNTs	GF=17.5	[111]
	PDMS/MWNTs	40.12 KPa^{-1}	[61]
	reCNT-PDMS	372.2 kPa^{-1}	[112]
	PDMS/AgNWs	2.04 kPa^{-1}	[66]
	PDMS/AgNWs/CNFs	——	[65]
	AgNWs/PDMS	——	[113]
	Mxene/CFs/PDMS	35.12 kPa^{-1}	[114]
	AgNWs/MXene/PDMS	0.812 kPa^{-1}	[115]
	PDMS/ MXene	39.3 kPa^{-1}	[116]
PU (CNTs AgNWs MXene)	PU/CNTs	——	[117]
	PU/CNTs-COOH	GF=17.5	[118]
	CNTs/PU/AgNPs	——	[119]
	PU/AgNWs	0.009 KPa^{-1}	[54]
	PU/AgNWs	6.258 KPa^{-1}	[120]
	PU/PDA/AgNWs	——	[121]
	MXene/TPU/PAN	0.208 KPa^{-1}	[122]
	MXene@PU	GF=0.7659	[123]
	MXene/polyurethane (PU)	150.6 KPa^{-1}	[124]
Fiber (CNTs AgNWs MXene)	CNTs/SNWF	GF=74	[125]
	CNTs/AgNPs@p-SF	GF=740	[126]
	Sericin–CNTs	——	[127]
	Silk fibroin/AgNWs	2.27 KPa^{-1}	[128]
	AgNWs/pSBS/ Fiber	5.2 KPa^{-1}	[129]
	AgNWs/Fiber	0.2 KPa^{-1}	[130]
	MXene/AgNWs/Fabric	14.28 KPa^{-1}	[131]
	Mxene/Paper	0.04 KPa^{-1}	[132]
	MXene/Fabric	6.31 KPa^{-1}	[133]
PVA (CNTs AgNWs MXene)	PVA/mCNT-OH	GF=2.52	[134]
	SWCNT/PVA	——	[135]
	PVA/SS@CNTs	GF=4.75	[136]
	PVA/AgNWs	——	[137]
	PVA/CMS/AgNWs	——	[138]
	PVA/AgNWs	——	[139]
	MXene/PVA	2320.9 kPa^{-1}	[140]
	PVA/MXene	0.45 kPa^{-1}	[141]
	GO/PVA/MXene	1.744 kPa^{-1}	[142]
PAM (CNTs AgNWs MXene)	PAAm/CNTs	GF=343	[143]
	CNTs/HAPAAm	GF=2	[53]
	PAM/CNTs	GF = 54.89	[144]
	Aam/AgNWs	——	[145]
	PAM/AgNWs	GF = 1.8	[146]
	PVA/TA/PAM/ AgNWs	——	[147]
	PAM/MXene	782.7 kPa^{-1}	[148]
	PAAm/SA/MXene	GF =7.4	[149]
	PAAm/PVA/MXene	GF =5.02	[150]

Table 4
Commercially available tactile sensors

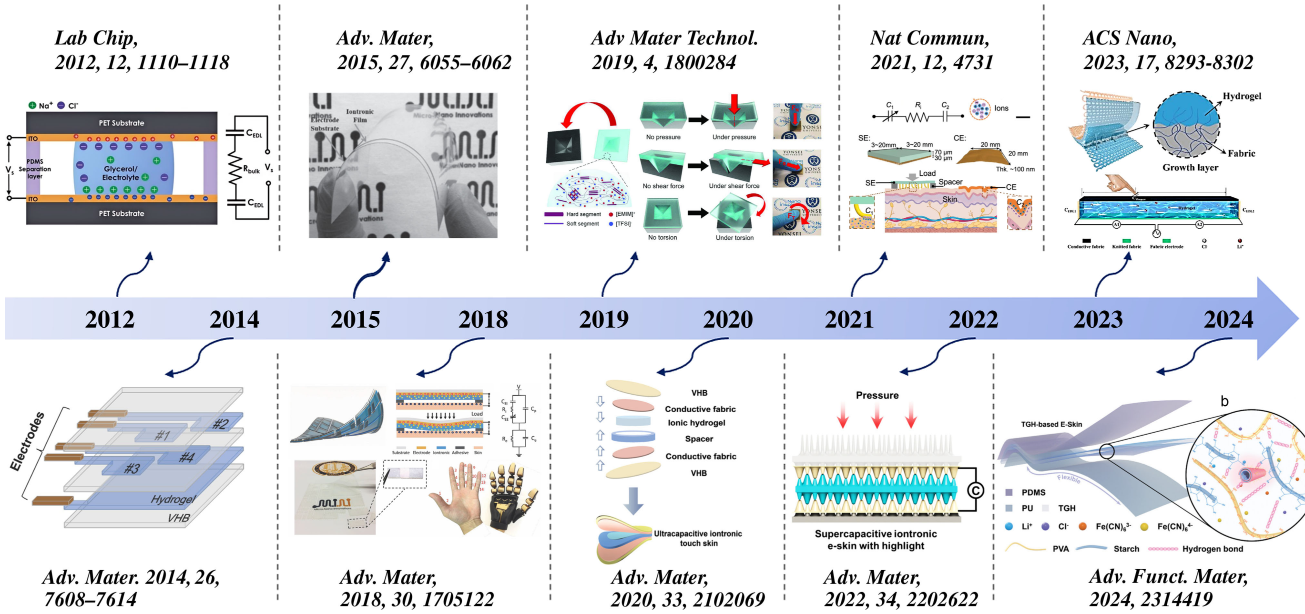
Sensing type	Schematic diagram	Company
Resistance		Suzhou Nengsda Electronic Technology Co., Ltd.
Capacitance		Suzhou Nengsda Electronic Technology Co., Ltd.
Piezoelectric		Suzhou Nengsda Electronic Technology Co., Ltd.
Resistance		Guangzhou Puhui Technology Co., Ltd.
Piezoelectric		Murata Manufacturing Co., Ltd.

The double electric layer structure formed by ions reduces the capacitance gap to the nanoscale (~1 nm), significantly increasing charge density and enhancing sensor sensitivity. This innovation overcame the traditional thickness limitations of capacitive sensors, optimizing performance by altering the electrode contact area rather than relying solely on thickness changes. Furthermore, the design of ion-droplet electronic sensors has opened new research directions for the application of ionic gels and ionic droplets. Ionic gels, as a new material, have shown significant advantages in flexible sensors. In 2014, Sun et al. [152] proposed an ion-based hydrogel capacitive sensor with excellent mechanical flexibility and transparency, capable of detecting tiny pressure changes, and demonstrated the key role of ionic materials in improving sensor performance.

2.5.1. The development of ion-electronic sensors

The term "iontronic" officially entered the research field of flexible pressure sensors. Nie et al. [153] developed an ion-electronic microdroplet sensor with extremely high sensitivity, reaching 0.43 nF/kPa. Compared to traditional parallel-plate capacitive sensors, this sensor significantly improved the response sensitivity between pressure and capacitance through the double electric layer mechanism of ionic materials such as ionic liquids, ionic gels, or ionic nanofibers. In 2015, Nie et al. [154] successfully replaced ionic droplets with ionic gels as the medium, overcoming the instability of droplets while maintaining the high conductivity of ionic liquids and offering better mechanical stability. The new design of the ionic electronic thin-film sensor demonstrated extremely high capacitance per unit area (5.4 $\mu F/cm^2$) and ultra-high sensitivity (3.1 nF/kPa), with sensitivity over 1,000 times that of traditional solid-state sensors [154]. In 2018, Zhu et al. [155] combined a single-sided ion-electronic device with skin, proposing a novel pressure sensor architecture for wearable sensor applications. This architecture utilized the epidermal-ion-electronic interface and exhibited high adaptability under ultra-thin packaging (1.9 μm), effectively detecting internal and external mechanical stimuli [155]. In 2019, Choi et al. [156] fabricated a pyramid-shaped ionic gel structure that can detect both pressure and shear force, with high sensitivity and a wide range of detection capabilities. In 2021, Shen et al. [157] developed a supercapacitive tactile sensor using hydrogels and arranged it in an array for robotic surfaces, achieving high sensitivity and resolution. In 2021, Zhu et al. [158] implemented pressure sensing through the buckling instability structure of elongated micro-pillars and replaced ionic materials with human skin, ensuring excellent biocompatibility. This ion interface holds great potential for intelligent epidermal monitoring and medical devices [158]. In 2022, Niu et al. [159] combined the triboelectric effect and ion-electronic

Figure 3
The development and application of ion-electronic mechanism-based sensors



mechanisms to fabricate a bionic hair-like structure with dual-interlocking microcone electronic skin, applied to both static and dynamic tactile sensing, and conducted experiments on tactile gloves for sign language recognition and robot interaction. In 2023, Xu et al. [160] developed a stretchable ion-electronic touchscreen panel with good touch sensing resolution, suitable for handwriting interaction, gaming control, and expanding research on ion-electronic mechanisms in wearable fields. In 2024, Li et al. [161] also utilized hydrogels as human-machine interface layers, fabricating stretchable, high-ion-conductivity hydrogel structures combined with machine learning for recognition and authentication, showcasing the immense potential of ionic conductive layers in human-machine interactions (Figure 3).

2.5.2. Microstructural ion-electronic pressure sensing

Microstructural design plays a crucial role in enhancing the performance of tactile sensors. By optimizing the microstructure, the sensitivity and response speed of the sensor can be significantly improved. Microstructure design typically involves controlling the deformation capacity of the sensor and the electrode contact area, both of which influence the sensor's performance.

For instance, pyramid-shaped microstructures take advantage of the compressibility of air in the pores to enhance the deformation ability while reducing the electrode contact area, thereby improving the response speed. Novel microstructures, such as micro-domes and interlocking structures, are widely used in piezoelectric and triboelectric sensors, contributing to improved sensitivity and accuracy. The micro-dome design enables the sensor to deform easily under pressure, enhancing its sensitivity to minute pressure changes.

In 2014, Tee et al. [162] introduced pyramid microstructures to enhance the device's deformation capacity through the compressibility of air in the pores, while reducing the electrode contact and adhesion area to increase response speed. Following this, micro-domes [19, 163, 164], porous structures [165–168], and interlocking microstructures [169–171] have been widely applied in capacitive, resistive, and triboelectric sensing mechanisms. Despite the effective enhancement of sensitivity and response speed with the introduction of microstructures, the sensor's working mechanism often relies on the deformation of the intermediate layer. Thus, even with microstructural incorporation, there remain certain limitations in sensitivity and response speed. In this context, the application of microstructures in ion-electronic sensors has been further optimized. In 2018, Qiu et al. [172] reported a low-cost microstructural ion gel (MIG), which features a uniform conical surface microstructure, effectively enhancing the sensor's sensitivity and response range. The MIG film was patterned using soft lithography from the leaves of *Calathea zebrina* and integrated with a flexible electrode interlayer, maintaining excellent sensitivity across a wide range from 0.1 Pa to 115 kPa. The microstructure optimization allows the device to maintain high sensitivity even under low-pressure conditions, making it suitable for haptic perception in human-machine interaction applications [172].

In 2022, Tang et al. [173] proposed a TIS device architecture that achieves high sensitivity and excellent optical transparency. This device employs a two-layer sensing structure combining transparent AgNw conductive films with a microscopic hemispherical transparent ion elastomer array, with a nonionic liquid filling between the ion electrodes and counter electrodes. This design not only maintains the high sensitivity of the device but also enables dual optical and tactile functions without compromising transparency, making it capable of evaluating tissue stiffness during endoscopic imaging [173].

In 2020, Bai et al. [93] introduced a graded, fillable microstructure (GIA) design that significantly improves sensitivity and extends the pressure response range. The GIA structure accommodates deformed surface microstructures via undercuts and grooves, enhancing compressibility and pressure response range. It demonstrates extremely high sensitivity and ultra-high resolution across a broad pressure range from 0.08 Pa to 360 kPa while maintaining significant mechanical stability [93]. In 2022, Guo et al. [174] proposed an integrated hybrid device based on ion sensing and electrochromic display for interactive pressure sensing. The device uses capacitance changes in the ion gel layer to achieve highly sensitive pressure detection with a large capacitance response range. The introduction of microstructures improves the contact area between the electrodes and the gel, increasing the electrical double-layer (EDL) capacitance and allowing the sensor to maintain high sensitivity over a wider pressure range [174]. In 2023, Guo et al. [175] used a simple photopolymerization process to fabricate crosslinked ion hydrogels, integrating them into a wireless monitoring system as a pressure sensor application. Unlike conventional capacitive pressure sensors, ion-electronic sensors replace the insulating dielectric layer with an ion hydrogel layer, enhancing sensitivity through the EDL formed at the electrode-ion membrane interface. This design enables high noise immunity and significant signal enhancement in complex dynamic environments [175].

In 2022, Bai et al. [176] further optimized flexible ion-electronic pressure sensors by incorporating micro-pillars to improve sensitivity and linear response. The micro-pillar design effectively enhances the structure's compressibility, evenly distributes stress, prevents signal saturation, and increases the initial contact area, ultimately achieving high sensitivity (49.1 kPa^{-1}) and good linearity [176] (Figure 4 [93, 172–176]).

2.6. Multifunctional sensing systems

Multifunctional sensing systems integrate different types of sensors (such as temperature [177–179], slide [180–182], humidity) [183–185] to simultaneously detect various physical and chemical stimuli. These systems are particularly suitable for fields like human-machine interaction and robotic perception, where they can significantly enhance sensing accuracy and response speed. When designing multimodal sensing systems, a common approach is to integrate multiple sensors into a single platform, creating a multifunctional sensing system. By responding to multiple input stimuli, these systems effectively simplify the device structure and reduce system complexity.

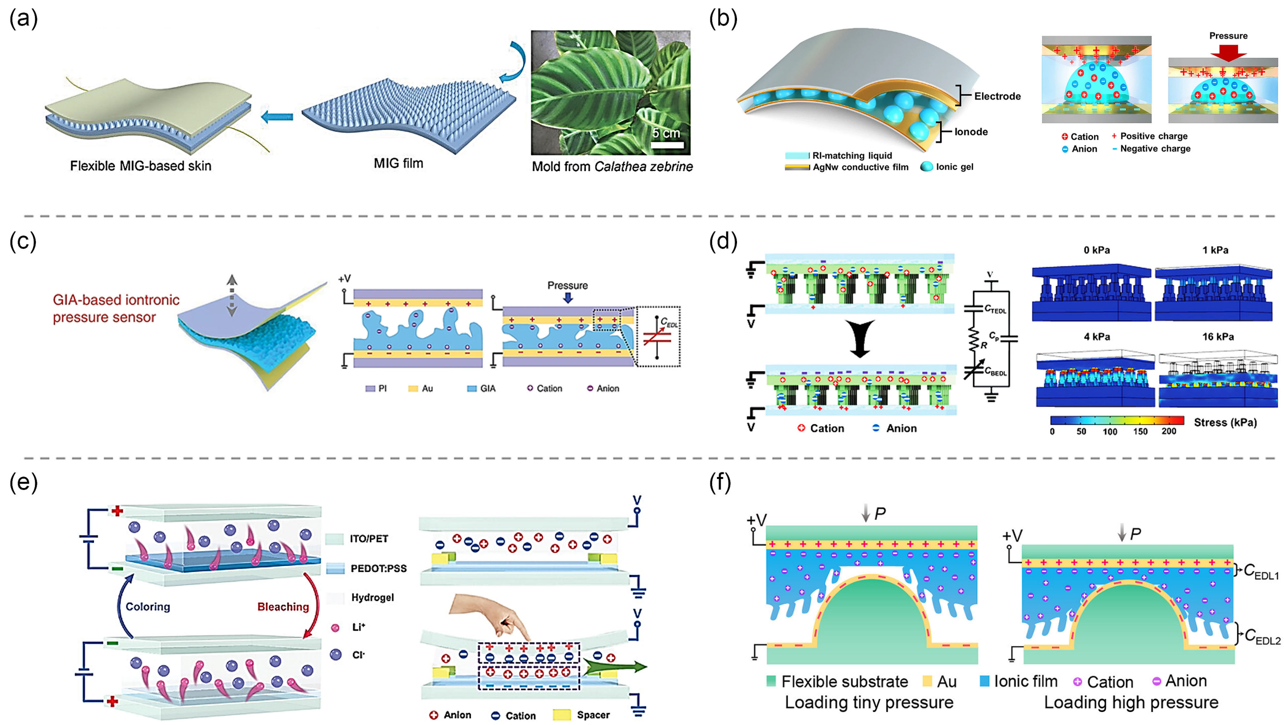
For example, in the design of pressure-temperature dual-functional sensors, the capacitance and resistance changes of a single sensing element can simultaneously respond to different stimuli from temperature and pressure, thereby simplifying the device structure and reducing the complexity of the measurement system. In this process, neural networks can efficiently extract useful information from mixed signals. Ren et al. [186] successfully achieved dual sensing of temperature and pressure using a gradient ion gel via an electric field-induced strategy. By employing the Vogel-Tamman-Fulcher equation, they established the relationship between capacitance, temperature, and pressure, significantly improving the sensor's measurement accuracy [186].

Machine learning algorithms also play an important role in multimodal sensor systems. Ren et al. [186] leveraged the unique response characteristics of capacitance and resistance to changes in temperature and pressure to achieve synchronous measurement of both temperature and pressure. They used neural network technology as a data processing method to establish a mapping between capacitance/resistance signals and pressure/temperature, thus enabling high-precision calibration of the sensors [94].

Ding et al. [185] fabricated a pressure/proximity dual-mode sensor using a template method. By utilizing the sensitivity differences between pressure sensing and proximity sensing, they achieved crosstalk-free detection and differentiation, offering potential applications in robotic touch and human-machine interaction. Chen et al. [187] developed a pressure-temperature-proximity sensor using

Figure 4

Microstructure devices: (a) structural diagram of conical leaf template, (b) schematic diagram of micro-dome structural layer, (c) schematic diagram of filling structure of sandpaper template, (d) schematic diagram of hollow and microcolumn structural layer, (e) schematic diagram of hollow structural layer, and (f) interlocking fill structure layer diagram



ion gel fibers. With the assistance of the EDL effect, they achieved highly sensitive pressure sensing, while temperature sensing was enabled through the dielectric constant of the gel layer. Proximity detection was realized via changes in the electric field. This design provides new insights for the application of ion-electronic mechanism sensors in the wearable field. Zhu et al. [188] proposed a triboelectric-based technology capable of detecting bending and sliding in multiple directions and developed a haptic feedback glove on this basis, using machine learning to assist in object recognition tasks. These innovations showcase the vast potential applications of multimodal sensor systems in smart devices and human-machine interaction. Another type of multi-sensor system integrates different sensor types into the same platform to form multimodal perception. One effective strategy is to carefully select materials suited to specific stimuli to differentiate various types of signals. Ge et al. [189] proposed a low-coupling multifunctional electronic skin capable of simultaneously sensing proximity, pressure, temperature, and relative humidity, demonstrating its potential in multimodal perception. Zhang et al. [190] developed a stretchable sensor that can recognize various stimuli such as in-plane strain, temperature, and pressure. These three different sensory functions were achieved using a mechanical color-changing layer, a thermal resistance layer, and a triboelectric layer, respectively, each utilizing their unique materials and mechanisms to decouple different sensory signals. The integration and optimization of these technologies have greatly enhanced the performance of sensor systems, making the detection of various physical and chemical stimuli more precise. By achieving high-performance, multifunctional tactile sensor systems, these advancements have not only promoted the application of sensor technologies in multiple fields but also provided more accurate and reliable perceptual capabilities for various smart devices (Figure 5 [94, 185, 186, 189, 190]).

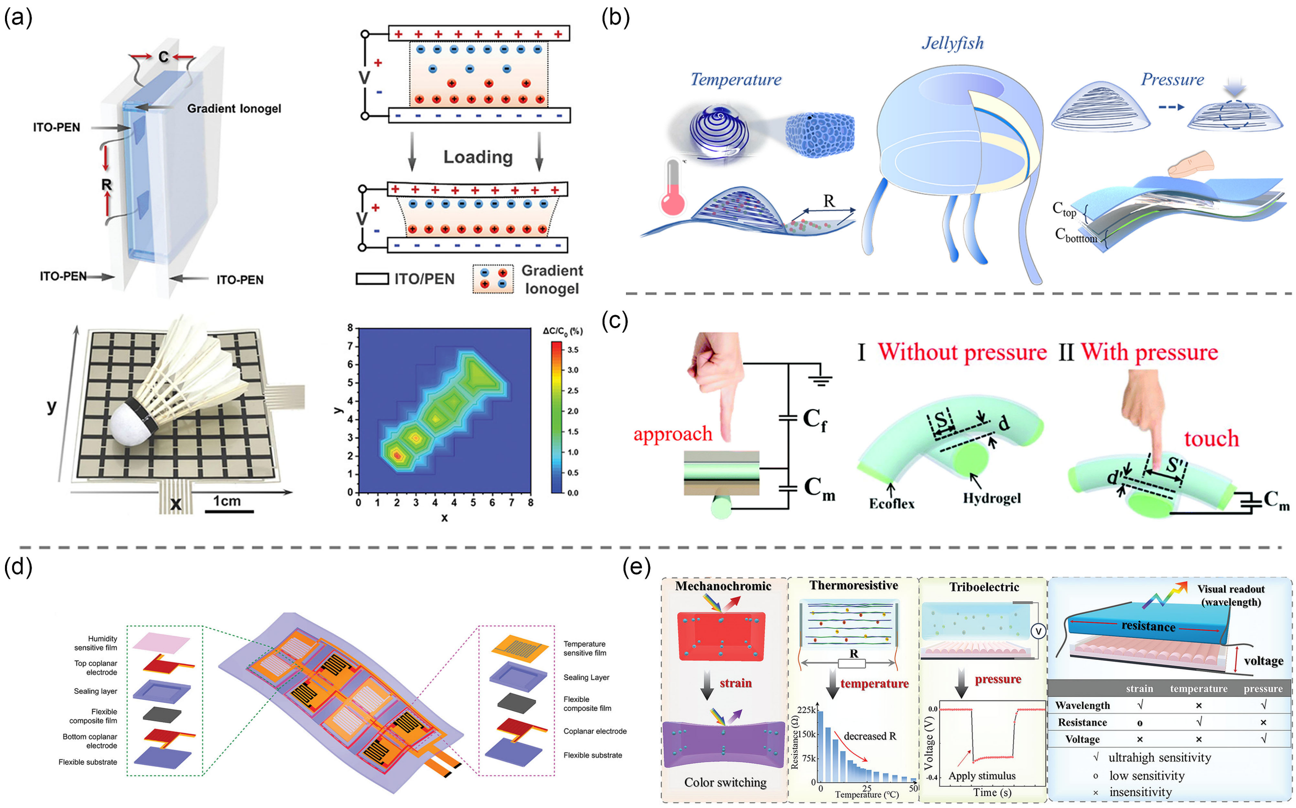
3. Technological Advances and Challenges of Tactile Sensors in Robotic Surface Applications

Tactile perception is a core capability for robots to interact with their environment and perform fine manipulation tasks. In recent years, significant breakthroughs have been made by integrating new sensor designs with artificial intelligence algorithms. The integration of tactile sensors on robotic surfaces has not only enhanced the adaptability and safety of grasping operations but also provided solid technical support for multimodal perception in complex scenarios.

3.1. Application of tactile sensors in robotic grasping control

Traditional robotic grasping relies on visual feedback, but often lacks real-time sensing of tactile information, such as contact forces and material properties. Sundaram et al. [191] proposed a solution based on a scalable tactile glove (containing 548 sensors). This system uses piezoelectric films and conductive fiber networks to create a distributed sensor network, combined with deep convolutional neural networks to perform object recognition, weight estimation, and tactile pattern analysis. The resulting dataset of 135,000 frames of full-hand tactile data provides an

Figure 5
Multifunctional sensor device: (a) capacitor and resistor signals are used to achieve temperature-pressure sensing, (b) bionic jellyfish structures use different sensitivity to achieve pressure-temperature sensing, (c) only capacitive signals are used to achieve pressure-proximity sensing, (d) vertical integrated pressure-temperature-approximation-humidity sensing diagram, and (e) strain-temperature-pressure sensor with tensile properties



important research benchmark in the field of tactile perception [191]. Similarly, Shen et al. [157] introduced a novel touch skin based on supercapacitive sensing, which combines ion-based hydrogels with conductive fabrics. This significantly enhances the sensitivity and tactile feedback of robotic hands, opening up broad prospects for applications in industrial robots and prosthetics.

Furthermore, Shi et al. [192] present a tactile sensor array based on an ion-electronic mechanism for robotic surfaces, effectively suppressing signal crosstalk while maintaining high-performance pressure sensing. This advancement holds great potential for tactile feedback in robotics and pressure detection in aerospace applications [192].

3.2. The role of tactile sensing in material recognition and operational adaptability

The robot's ability to perceive material properties (e.g., softness, roughness) is critical to performing safe operations. Qu et al. [193] described the development of a smart finger using the triboelectric effect, which generates a unique triboelectric fingerprint upon material contact (with an accuracy rate of 96.8%). This approach enables the dual recognition of material types and surface roughness. These breakthroughs not only overcome the limitations of traditional tactile sensors that only measure physical parameters but also pave the way for the perception of psychological parameters in robotic operations, such as tactile texture recognition [193].

Qiu et al. [194] proposed a non-invasive method for quantifying the elastic modulus of soft materials using a multi-sensory electronic skin and improved machine learning algorithms. By utilizing the synergistic mechanism of piezoelectric signals and strain feedback, the robotic hand can dynamically adjust its grasping force based on the object's softness (ranging from kPa to MPa), successfully applied to sorting fragile items (such as fruits of varying freshness) [194] (Figure 6 [157, 191–194]).

3.3. Integrated development of multimodal tactile sensing systems

The integration of tactile sensors with other perception modules is driving the multifunctional development of robots. Yu et al. [195] presented a flexible physical and chemical sensor array (M-BOT system) fabricated using inkjet printing technology, which combines tactile sensing, electrophysiological signal detection, and chemical hazard identification. By applying machine learning algorithms to analyze surface electromyographic signals and tactile feedback, the system can make autonomous decisions and issue threat warnings in contaminated environments. Such multimodal integration technologies not only expand the application boundaries of tactile sensors (e.g., in explosive detection and pathogen screening) but also introduce a new mode of interaction for remote robot operation in extreme environments [195].

Liu et al. [196] proposed a closed-loop human-machine interface system based on skin-integrated electronics, which integrates tactile feedback and visual signals, and enables wireless motion capture via Bluetooth, Wi-Fi, and the Internet. This system shows great potential in non-contact biological sample collection and the care of patients with infectious diseases. Its innovation lies in enhancing remote robotic control through tactile feedback, playing a significant role in improving remote control precision [196].

Figure 6

Robotic tactile sensing: (a) scalable haptic gloves with distributed sensing systems, (b) hydrogel array devices for robotics and prosthetics, (c) ion-electron mechanism array applied to the surface of robotic wrist, (d) triboelectric mechanism enables material type and roughness identification, and (e) piezoelectric signal and strain feedback are used together to sort fragile items feedback

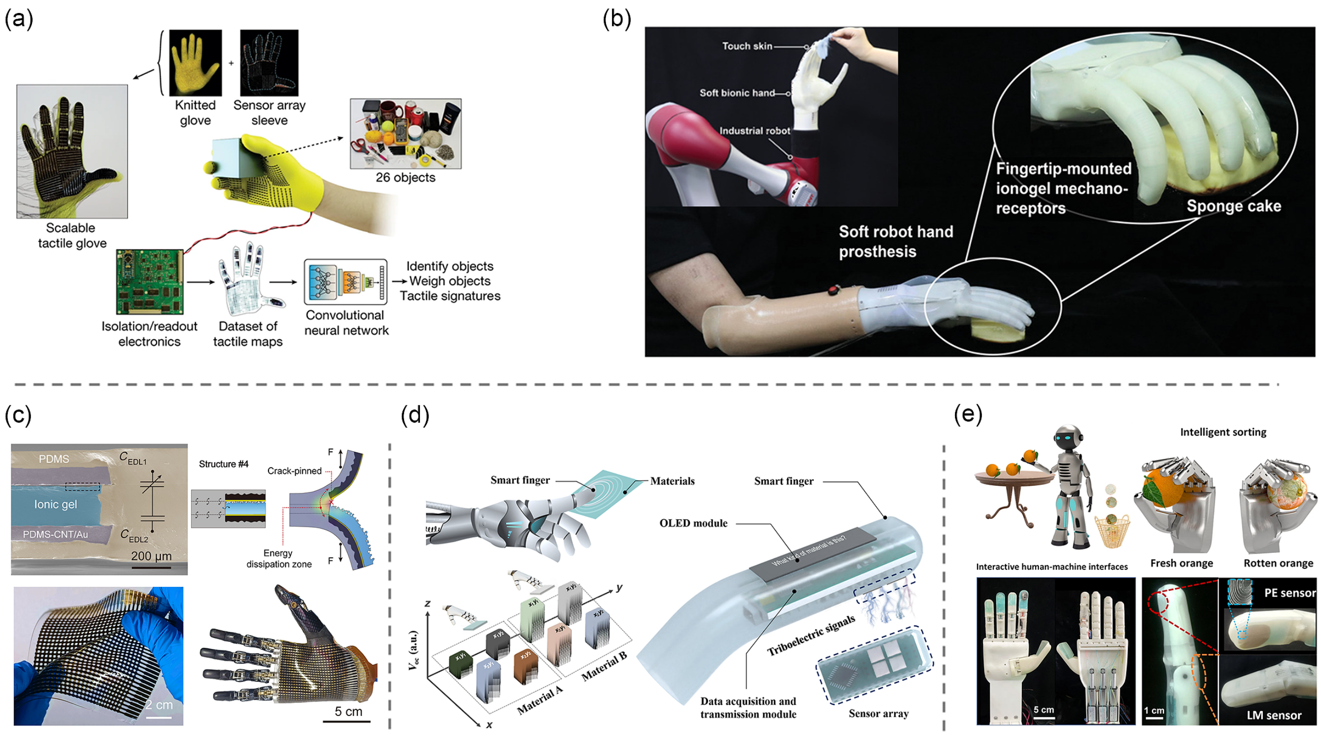
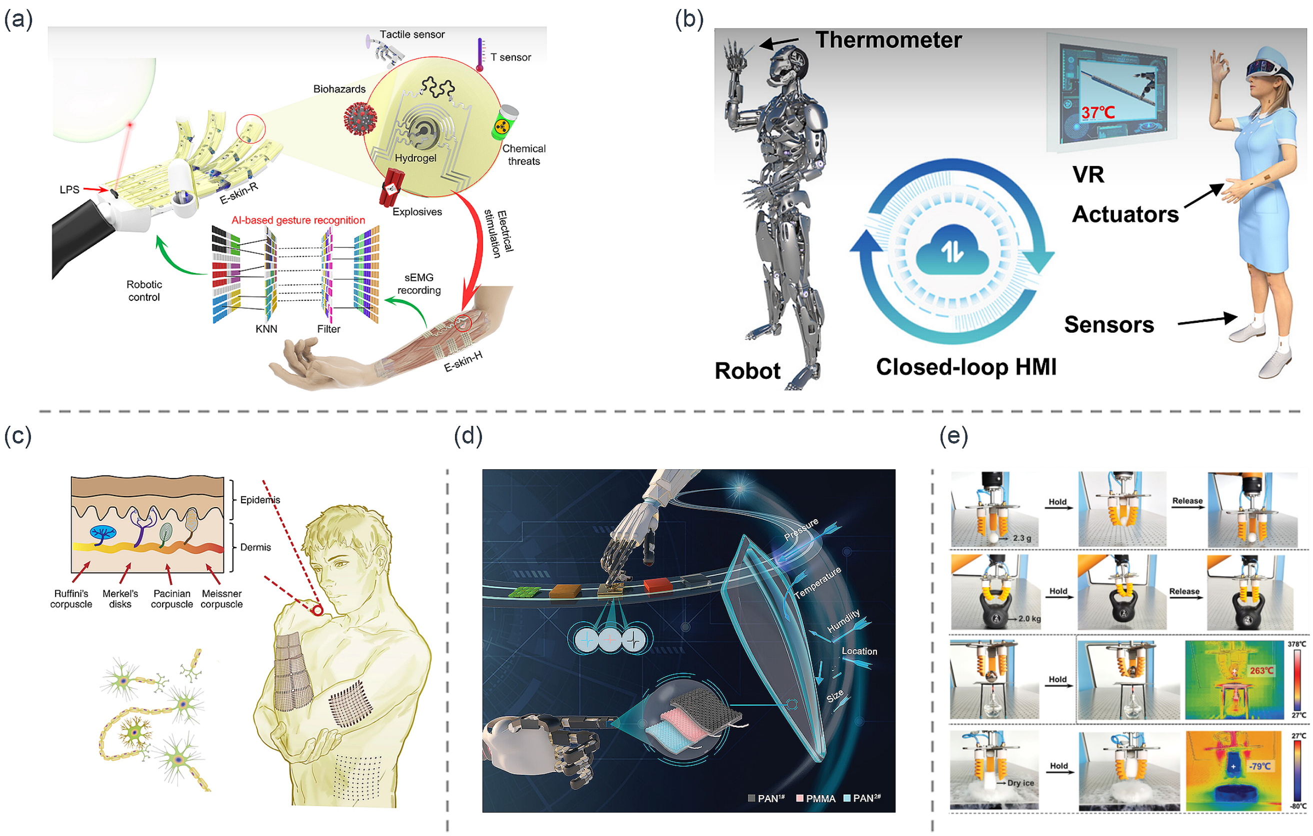


Figure 7

Integration of tactile sensing on robot surfaces: (a) sensor integrating tactile perception, electrophysiological signals, and chemical hazard identification, (b) closed-loop human-machine interface system for enhanced remote operation capabilities, (c) temperature-humidity-light-magnetic field multi-dimensional perception, (d) tactile sensing system for stable material identification, and (e) fingertip-inspired gradient ion gel sensors for grasping under extreme conditions



In the field of multimodal sensing, Hua et al. [197] introduce electronic skin based on a polyimide network, successfully extending the sensory capabilities of E-Skin to multiple dimensions, including temperature, humidity, light, and magnetic fields.

Wei et al. [198] demonstrated an intelligent tactile sensing system combining TENG and deep learning technology, which can reliably identify materials under various contact conditions, achieving an accuracy rate of 96.62%. This system has promising applications in bionic prosthetics and virtual space construction [198].

Ren et al. [186] presented a flexible sensor based on gradient ionic gels, inspired by the structure of human fingertip skin, exhibiting high sensitivity and a wide detection range (3×10^2 to 2.5×10^6 Pa), while maintaining excellent performance under extreme conditions (from −108°C to 300°C). This sensor has significant potential in intelligent grasping systems, capable of adapting to diverse tactile tasks in complex environments [186] (Figure 7 [186, 195–198]).

3.4. Current challenges and future directions

Despite significant advancements in tactile sensing technology, several key challenges remain, including the balance between sensor density and flexibility, bottlenecks in multimodal data fusion, the need for modeling tactile psychophysical parameters, environmental adaptability issues, and limitations in low-cost integration. Future research should focus on the development of biomimetic materials, such as self-healing conductive polymers and smart nanomaterials, to enhance durability and adaptability; the integration of neuromorphic computing chips for embedded processing to optimize real-time tactile perception data; the creation of cross-modal perception frameworks to improve robots' environmental adaptability; large-scale manufacturing of flexible electronic skins to achieve low-cost and high-performance tactile sensing; and AI-driven intelligent tactile interactions to enhance tactile recognition capabilities, thereby advancing fields like biomimetic prosthetics and smart gloves [199–202].

4. Conclusion

As robotics technology continues to evolve toward greater autonomy and intelligence, tactile sensing systems have become one of the key technologies for overcoming the interaction bottleneck between robots and complex environments. The sensitivity, multimodal perception capabilities, and environmental adaptability of tactile sensors directly impact the operational precision and adaptability of robotic systems across various application scenarios. This is particularly important in fields such as precision surgery, minimally invasive operations, and complex industrial manufacturing, where tactile sensors capable of providing real-time, precise force feedback are becoming increasingly vital in robotic perception systems.

Currently, the rigid structure, limited sensitivity, and single-modal perception of traditional tactile sensors restrict their application in complex interactive scenarios. In recent years, tactile sensor technologies based on flexible electronic materials and biomimetic microstructure designs have offered new solutions to address these challenges. The emergence of novel sensing materials, such as ionic gels and flexible electronic skin, has significantly enhanced the sensitivity, response speed, and adaptability of sensors, driving their widespread application in fields like healthcare, industry, and wearable devices. Different types of sensors, such as resistive, capacitive, piezoelectric, and triboelectric sensors, each exhibit unique advantages in their respective applications, with piezoelectric and triboelectric sensors particularly excelling in dynamic response and texture recognition.

However, despite some progress, tactile sensing technology still faces numerous challenges. For instance, enhancing the multimodal perception ability of sensors and improving their accuracy in sensing complex mechanical parameters (such as normal and shear forces) remain hot research topics. Furthermore, the high sensitivity and fast response characteristics of sensors may encounter issues of flexibility and stability in large-scale applications, requiring further optimization through material innovations and microstructure designs.

Future research directions may focus on several key areas: First, enhancing the sensitivity and environmental adaptability of sensors through the use of flexible materials and biomimetic designs, second, integrating multimodal sensing systems to enable the simultaneous detection of multiple physical or chemical parameters on a single sensor platform, thereby improving the comprehensiveness and precision of robotic perception. Finally, combining machine learning and intelligent algorithms for sensor data processing could significantly enhance the system's adaptability and intelligence, making tactile sensing technology more suitable for complex and dynamic working environments.

Overall, with the continuous advancement of flexible materials, sensor designs, and intelligent algorithms, tactile sensors are expected to play an increasingly important role in future robotic perception systems, providing strong support for the further development of robotics technology.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

PingAn Hu is the Editor-in-Chief for *Smart Wearable Technology* and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Huiwen Ren: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Wangyang Li:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Yanan Ding:** Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Yuming Feng:** Writing – original draft. **Hexin Li:** Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Jianyang Li:** Writing – original draft, Writing – review & editing. **Jia Zhang:** Writing – original draft, Writing – review & editing, Supervision. **Haiying Xiao:** Writing – original draft, Writing – review & editing. **Jialu Li:** Writing – original draft, Writing – review & editing. **Shuai Wang:** Writing – original draft. **Cong Huang:** Writing – original draft, Writing – review & editing, Supervision. **Li Jiang:** Writing – original draft, Writing – review & editing, Supervision. **PingAn Hu:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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