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Bio-inspired microstructures for high-performance and self-powered E-skin technologies

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ABSTRACT

The advancement of electronic skin (e-skin) technology has transitioned from fictional narratives to real-world applications due to breakthroughs in microelectronics. Current e-skin designs utilize advanced materials and microfabrication techniques. Recent developments focus on integrating biomimetic microstructures, such as pyramids, domes, and nanofibers, to enhance sensor performance. These structures improve sensitivity, flexibility, and durability. Innovations include self-powered sensors using piezoelectric materials like PVDF and ZnO, as well as multi-mode e-skins combining capacitive and piezoelectric sensors, stretchable electrodes, and self-healing materials. E-skin technology has applications in wearable devices, healthcare, robotics, and human-machine interfaces. This review, using the PRISMA methodology, examines advancements in tactile sensors, highlighting the role of biomimetic microstructures. These structures provide additional functionalities such as freeze resistance, corrosion resistance, self-cleaning, and degradability, optimizing overall sensor performance. Continued research and innovation are moving e-skin technology towards human-like tactile sensing with improved performance, flexibility, and self-sufficiency. This review summarizes the latest developments in biomimetic microstructures for tactile sensors and their application prospects in human detection and human-machine interaction devices.

1. Introduction

The concept of artificial skin, or "E-skin," has been inspired by various sources, including science fiction works like Caidin's "Cyborg" and George Lucas's Star Wars series, which envisioned characters with electronic body part replacements [1]. Real-world improvements in microelectronics have emerged in response to these fictional concepts, leading to significant progress in the field of artificial skin, such as prosthetic hand with discrete sensor feedback which developed by Clippinger et al. in 1974 [2]. Electronic skin (e-skin) technology strives to mimic the human skin's remarkable ability to perceive touch [3]. Tactile sensing in the skin relies on specialized neuronal elements known as mechanoreceptors that transduce mechanical stimuli into electrical signals [4], situated at different depths beneath the skin surface, responding to forces on various timescales [5]. The skin contains around 17,000 mechanoreceptors, including Meissner's Corpuscles, Merkel Disks, Ruffini Organs, and Pacinian Corpuscles crucial for tactile sensing and distributed throughout the body, exhibiting varying density [6]. However, a few obstacles could be found that could prevent meaningful progress in this important area of science [7]. To begin, the lack of a specialized sensory organ in tactile sensing [8], Second, tactile sensing is complex, making it difficult to find suitable technological

analogies, the nature of tactile sensing through the skin involves more than simply transducing one physical property into an electronic signal. This complication stems from various modalities such as temperature, texture, shape, force, friction, and pain, and other physical properties That is spread throughout the skin [8,9]. Third, there are Challenges in data gathering arise from the poorly defined nature of the touch signal, in contrast to the visual and aural senses [10-12]. These receptors display distinct rates of adaptation, where the rate of adaptation relates to how quickly the mechanoreceptor pulse rate returns to normal after a change in stimuli [13]. Fast-adapting (FA) mechanoreceptors detect dynamic force changes and generate powerful signals during force application or removal [10]. Slow adapting (SA) mechanoreceptors, on the other hand, perceive static stresses and provide constant responses throughout extended stimulation[14,15]. Despite these challenges, significant progress has been made in the field of e-skin. Researchers have developed various transduction mechanisms and material innovations, including resistive, capacitive, piezoelectric, and triboelectric modes of operation. Each method offers unique benefits in sensitivity, flexibility, and energy efficiency, making them suitable for diverse applications in robotics, healthcare, and human-machine interfaces [16]. Capacitive tactile sensors, for example, are crucial in robotics, human-machine interaction and e-skins technology. They detect capacitance changes

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caused by the deformation of dielectric materials between electrodes, with enhancements achieved through microstructures surfaces and advanced materials like polydimethylsiloxane (PDMS) and graphene [17,18]. Thus exhibits high sensitivity, often in the range of 0.145–1.194 kPa⁻¹, with testing ranges extending to 80 kPa for force detection [19, 20]. Piezoresistive e-skins, known for their simplicity and wide range of pressure detection by measuring changes in electrical resistance due to mechanical deformation. Offering high sensitivity and enabling strain detection up to 650 % [21,22]. however, they can experience temperature sensitivity and hysteresis issues [23]. Recent innovations have focused on developing flexible composite materials with self-healing properties and bio-inspired designs that mimic natural tissues [24]. Triboelectric nanogenerators (TEGs) represent a novel approach, utilizing the triboelectric effect to generate electrical energy from mechanical stimuli. TENGs have shown considerable promise in energy harvesting and e-skins self-powered sensing applications, thanks to their high output performance, high sensitivity flexibility, and ecological compatibility [25]. Advances in material selection, surface roughness, and bio-inspired designs have further enhanced the sensitivity and durability of these devices, making them suitable for a wide range of applications, from wearable electronics to underwater detection systems [26]. Furthermore, advances in integrated materials and micro-fabrication are essential for developing artificial skins with integrated tactile sensing for multifunctional e-skin applications. This entails the use of combinations of materials that have high flexibility, sensitivity, and excellent piezoelectric coefficients, such as polyvinylidene difluoride (PVDF) and zinc oxide (ZnO) The integration of stretchable, biocompatible materials like graphene, carbon nanotubes (CNTs), and PDMS is critical for modern tactile sensor technology [27]. These materials enable e-skins to detect a broad spectrum of stimuli while maintaining flexibility and durability. Notably, Ryu et al have developed e-skins that can simultaneously mimic SA- and FA-mechanoreceptors, crucial for applications in wearable healthcare devices, humanoid robotics, and artificial prosthetics [28]. Suo and Rogers have made achievements in stretchy electrodes and flexible electronics, converting normally brittle materials through ultrathin (100 nm) sheets joined by stretchable interconnects [29,30]. The novel contribution of this review lies in its detailed examination of how biomimetic microstructures contribute to the overall performance optimization of tactile sensors. By focusing on the integration of these microstructures, the review offers a unique perspective on how sensor technology can be advanced beyond traditional approaches. Specifically, the emphasis on self-powered sensors using piezoelectric materials like PVDF and ZnO marks a significant innovation, enabling e-skins to operate without external power sources and seeks to overcome limitations in sensitivity, durability, and environmental adaptability [20].

The review also introduces the concept of multi-mode e-skins, which combine different sensing mechanisms—such as capacitive and piezoelectric sensors—with advanced materials like stretchable electrodes and self-healing materials, pushing the boundaries of what e-skin technology can achieve. Several investigations on pressure sensor arrays have been conducted, including work by Mansfield et al. [14] and Schwartz et al. [31] from Bao's group, which demonstrated highly sensitive flexible electronic skins using microstructure capacitive sensors. skin sensors stretchability is limited despite their flexibility due to using Gold (Au) or indium tin oxide (ITO) electrodes [32]. Lipomi et al. [33] used transparent elastic carbon nanotube films on a PDMS substrate to create a skin-like pressure and strain sensor array, which can detect pressures as high as 50 kPa without stretching. Recently, researchers have concentrated on creating relatively affordable and high-performance touch sensors. Enhancing sensor structures or using photolithographic microstructure techniques, such as matrix, pyramid, hierarchical, and interlocking designs, can dramatically improve sensing performance and the entire efficiency of tactile sensors as shown in Fig. 1 [34]. This paper extends these surveys by examining the literature

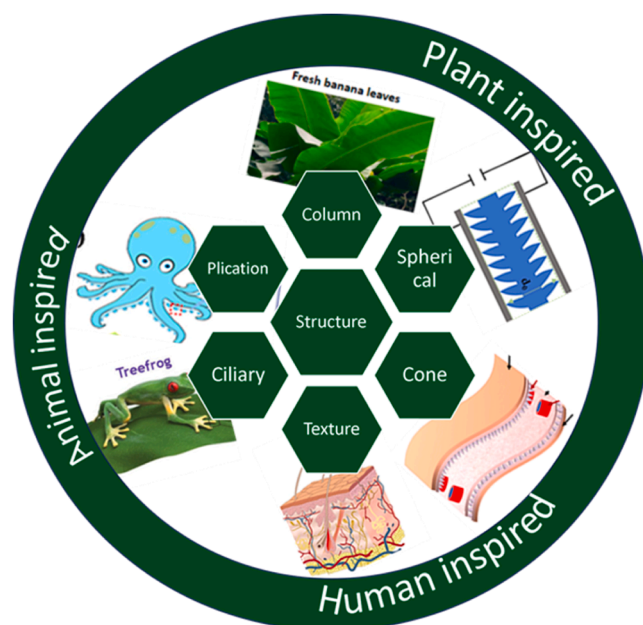


Fig. 1. depicts an overview of important tactile sensor structure based.

from the most recent five years. Building upon the earlier surveys, we explore basic principles, transduction mechanisms, materials in tactile sensor technology, and structural design. Additionally, applications in e-skin, HMI, and minimally invasive surgery, and robotics applications.

Methodology of conduction research

A well-known paradigm for performing systematic reviews is the PRISMA approach, which stands for Preferred Reporting Items for Systematic Reviews and Meta-Analyses. The PRISMA is method emphasizes transparency, accuracy, and bias reduction through a structured approach that includes defining research questions, establishing inclusion and exclusion criteria, identifying relevant literature, and systematically reviewing and analyzing data from multiple sources. Its key benefits include increased study validity, less reporting bias, and clearer, more trustworthy data synthesis. This method is very useful for synthesizing results from multiple investigations, making it suitable for analyzing improvements in tactile sensor technologies[35]. This research adopts the PRISMA methodology for a systematic literature review, focusing on tactile sensors. The review meticulously examines and categorizes selected works based on tactile sensor concepts, types, mechanisms, transducers, applications, features, and performance, utilizing publicly available databases. It concentrates on high-quality articles published within the five-year period of 2018–2023 to provide a deeper understanding of recent advancements in the field and identify key studies as shown in Fig. 2. The research topic, "Tactile sensors," was initially chosen, and specific keywords and tags were defined and applied to scientific databases such as Web of Science, Scopus, and IEEE as follows:

ScienceDirect: TITLE-ABS-KEY ("15 × 15 sensor array" OR "tactile sensor" OR "electronic skin" AND "Self-Powered" AND "Piezoelectric") AND PUBYEAR > 2017 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH")) AND (LIMIT-TO (EXACTKEYWORD, "Tactile Sensing") AND (LIMIT-TO (LANGUAGE, "English"))).

WOS: TS= (15 × 15 sensor array OR tactile sensor OR electronic skin) AND TS= (Piezoelectric AND Self-Powered) published between 2018 and 2023.

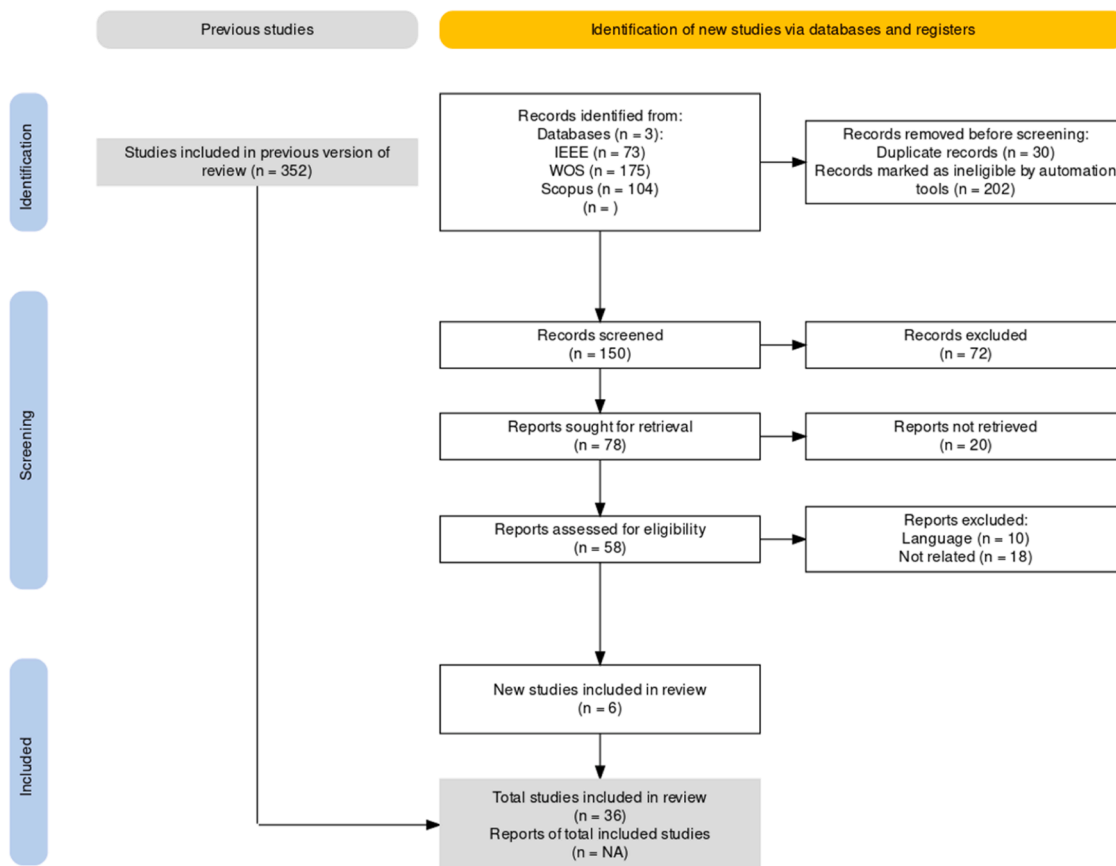


Fig. 2. The Categorization and selection process.

IEEE: "15 × 15 sensor array" OR "tactile sensor" OR "electronic skin" AND "Piezoelectric" AND "Self-Powered" published between 2018 and 2023.

A total of 352 documents were acquired through a search using specified keywords and tags. These papers were subjected to analysis. Exclusion criteria were applied to select relevant works for analysis, resulting in a curated collection of 30 papers, comprising journal articles, conference papers, a book, and reviews. Conference papers and the book were excluded from the categorization process, focusing solely on tactile sensors. The remaining works were divided into distinct categories to facilitate further analysis. The Structure of the review is organized as: Section 1 describes the brief introduction and the literature review. Section 2 describes the research methodology including search parameters and selection criteria. Section 3 examines the chosen works, categorizing them based on the types of tactile sensors mechanism and their applications., and Section 4 summarizes the information gathered and closes the review by discussing the future field's prospects.

3. Sensing mechanisms microstructure based

Many varieties of touch sensors have been employed for many applications and settings since researchers first began developing them. Here, the emphasis is on the intriguing practical uses for touch sensors. Samples of the primary tactile sensing technologies with various mechanisms are displayed in Table 1. This section provides an overview of the principles and architectures pertaining to sophisticated tactile sensors such as fiber Bragg grating, optics, piezoresistive, piezoelectric, and capacitive sensors. In general, all mechanisms aimed to converting the tactile stimuli into electric signals. Fig. 3 illustrates briefly the most common transductions methods that have been achieved.

3.1. Bio-microstructure capacitive mechanism

The fundamental structure of tactile sensors that use capacitive technology is as follows: a capacitive texel is made up of two opposing electrodes that are separated by a dielectric material and supported by an elastic structure as shown in Fig. (3. i). The capacitance of this texel, which represents the capacitor's ability to hold electrical charge, fluctuates in reaction to applied force or pressure [37]. This force can change the distance between capacitor parallel plates or their area, as indicated by the formula below:

$$C = \frac{\epsilon_0 \epsilon_r A}{d} \quad (1)$$

Where is C the Capacitance value, $\epsilon_0 \epsilon_r$ is the permittivity of Vacuum and the dielectric materials, A is the area between the electrodes, and d is the distance between the two parallel opposing electrodes. As a result, the compressibility of the dielectric materials in a capacitive sensor determines its sensitivity. When force is applied, the soft dielectric deforms, shortening the distance between electrodes and increasing total capacitance. [38]. This deformation alters the permittivity, reflecting a physical or chemical response to stimuli, which is evaluated by capacitance variations. As a result, the performance of capacitive sensors can be improved by creating dielectric materials with increased compressibility, such as porous architectures. Furthermore, adding various types of microstructure surfaces into the dielectric layer and at the interfaces, such as pyramids, domes, pillars, nanofibers with porous topologies, or high dielectric constant filler materials, might enhance performance [38]. Another way to improve performance is to use sophisticated electrode materials for capacitive sensors, such as polydimethylsiloxane (PDMS) [39], carbon nanotubes (CNTs) [33], and graphene [17]. For example, Lee developed a PDMS-based flexible

Table 1
Summary of mechanisms sensing, and the most common materials used.

Sensing Mechanisms	Structure	Materials (substrate/ electrode)	Measurement	Applications	Ref
Capacitive	Columnar	PLA/PDMS	Strain, pressure, position, and texture.	Soft robotics, prosthetics, wearable electronics, Human-machine interaction, Medical devices, E-skin, High-resolution touch sensors.	[45]
	Mesh	PDMS/CNTs			[81]
	Spherical	PDMS/ AgNWs			[46]
	Pyramid	PDMS/ OTFT			[31]
	Mesh	PDMS/Graphene			[82]
Piezoresistive	Convex sandwich	PDMS/MXene	Mechanical stimuli including normal, shear, stretch, bending, and twisting forces, pressure and slipping detection	Robotics, medical devices, and HIM, E-skin, touchscreens, and wearable devices.	[83]
	Micro-Patterned	PDMS/SWNTs			[84]
	Hetro-microstructure	PU/AgNWs			[63]
	Nanofibers	PDMS/ (PEDOT: PSS, PUD)			[85]
	Tree-like	Rubber/ (MXene, SWCNT, PVP)			[65]
Piezoelectric	hierarchical wrinkle	Graphene/Ecoflex	Response to Mechanical pressure, deformation (bending and stretching), tactile stimuli, static and dynamic sensing, Force.	Robotics, Wearable Electronics, Medical Devices, Industrial Automation, E-skin, HMI, soft robotics, prosthetic devices, haptic feedback devices, and touchscreens.	[21]
	Micro-patterned	PDMS/CNTs			[86]
	Baklava	(Kapton, Al)/(PZT/ PVDF)			[87]
	Non-uniform curvature	PDMS/PVDF			[88]
	Ciliary	PDMS/ (PVDF, Fe ₃ O ₄)			[89]
	Wrinkle-sandwich-like	(PI/Au)/ (CNTs, PDMS, PVDF)			[90]
	A patterned array	GaN/ZnO NWs, IOT			[91]
Triboelectric	Sandwich	(PET, PI) film/(P(VDF-TrFE)	Detect mechanical stimuli including Touch, Pressure, tactile stimuli, and Energy Harvesting	HMIs, robotics, wearable devices, healthcare, prosthetics, energy harvesting, IoT, and Automotive	[92, 93]
	Bionic frogs' croaking behavior	AgNWs/BaTiO ₃ NPs/PDMS/ AgNWs, BC			[94]
	Micro-nanostructure	PET/ Ag, EVA-PDMS			[95]
	Sandwiched	PDMS-PET/ ITO-PET			[96]
	Hierarchical-Sandwich-like	P(VDF-TrFE-PDMS)/AgNWs			[97]
Micro-cilia	PDMS, GO/ITO	[26]			
Petiole-nanoporous	PDMS-PVDF/ AI, NR	[98]			

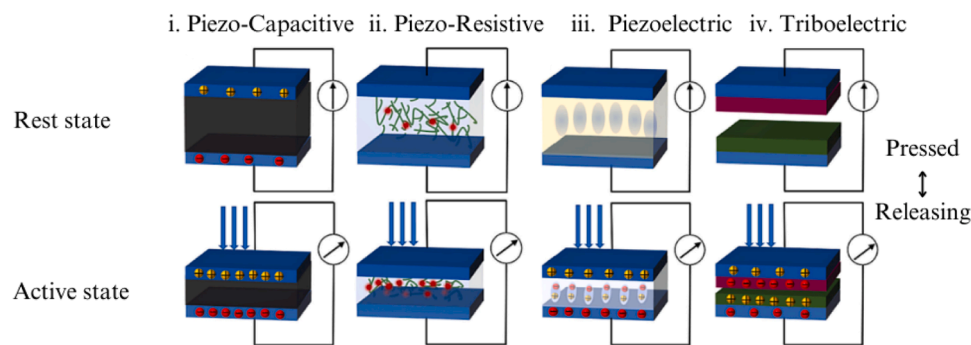


Fig. 3. Illustration for the common transduction mechanisms of tactile sensors: (I), piezoresistive, (II) capacitive, (III) piezoelectric, and (IV) triboelectric. Adapted [36].

tactile capacitive array capable of measuring both normal and shear force distribution [40].

For a capacitive strain sensor, the gauge factor (GF) is expressed as:

$$GF = \left(\frac{\Delta C/C_0}{\varepsilon} \right) \quad (2)$$

and for a capacitive pressure sensor, it is denoted as:

$$GF = \left(\frac{\Delta C/C_0}{P} \right) \quad (3)$$

where ε signifies strain, and P signifies pressure [41]. Capacitive sensors

have been popular in robotics because they have a simple structure with low power consumption, short dynamic response time, and minimal temperature effects making them highly desirable to create "taxes" that mimic some characteristics of human fingers' mechanoreception [42], despite their vulnerability to external fields [43]. Because capacitive sensors can be made tiny, they can be used to create dense sensor arrays and perform dynamic measurements. As shown in Fig. 4(b) Liu et al. developed a novel all-soft capacitive pressure sensor with a spine-pillar architecture inspired by the hierarchical organization of epidermal tissues [18]. This sensor's exceptional deformability and sensitivity of up to $2.87kPa^{-1}$ were accomplished by integrating random micron-scale spines with millimeter-scale pillar arrays composed of

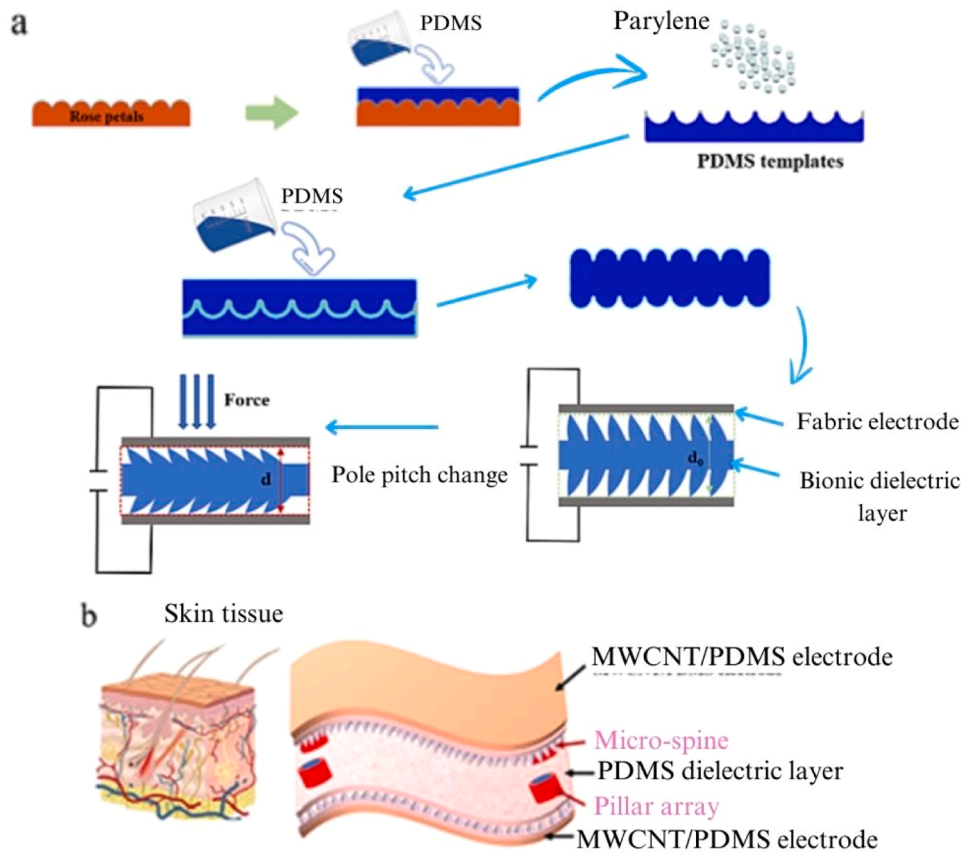


Fig. 4. presents two types of biomimetic capacitive microstructures for tactile sensors. Panel (a) shows a dielectric layer with a rose petal-inspired bionic structure Adopted [44]. Panel (b) illustrates the cross-section of human epidermal tissue alongside a proposed fully soft capacitive pressure sensor featuring a bionic spine-pillar microstructure [18].

polydimethylsiloxane (PDMS). Luo et al. introduced a capacitive flexible tactile sensor inspired by rose petals, featuring a sandwich structure based on a three-dimensional layered rib fabric Fig. 4(a)[44].

The fabrication involved creating a template with a complementary rose petal structure using a PDMS mixture. This resulted in dielectric layers with inclined rose petal structures on both sides, which were then assembled with a flexible fabric electrode layer embedded with rib fabric. The bionic fabric sensor demonstrated seven times higher sensitivity compared to a dielectric layer without microstructure. Additionally, it exhibited high sensitivity ($< 1kPa$, $0.145kPa^{-1}$) and a wide detection range ($0 - -80kPa$). Notably, the sensor could detect capacitance changes as small as $0.1pF$ at a pressure of $0.01N$, indicating its potential for motion monitoring and industrial applications. This bionic approach, inspired by the natural design of rose petals, is promising for developing more effective capacitive flexible sensors. Similarly, Guo et al. developed a capacitive tactile sensor based on octopus suction cups Fig. 5(e) [45].

This sensor features two conductive silver electrodes and a PDMS dielectric layer with an octopus sucker-inspired structure, fabricated through colloid self-assembly and spin coating methods. The innovative structure resulted in a sensor with high sensitivity of $0.636kPa^{-1}$ and a wide linear range from $8Pa - 500kPa$, making it suitable for high-precision wearable devices such as human-machine interaction devices, wearable electronics, and intelligent robots. Furthermore, Wan et al. leveraged the high aspect ratio and sparse microstructure of the lotus leaf to develop a flexible capacitive as shown in Fig. 5(a-d) [46]. The capacitive sensor was constructed by sandwiching a micropatterned bottom electrode, a CPI dielectric layer, and a top electrode. The obtained flexible tactile sensor exhibits a sensitivity of $1.194kPa^{-1}$ (when applied pressure $< 2kPa$), which is obviously higher than the

nonpatterned sensors. Furthermore, the flexible sensor is featured with a low limited of detection (LOD) $< 0.8Pa$, a fast response time within $36ms$, while showing no fatigue after $100000cycles$ of touching. Such high performance enables the flexible tactile sensor to detect the touching sense, limb motions, heartbeat, and gas flow. These studies illustrate that patterning the dielectric layer in capacitive sensors improves sensitivity and response range. However, the viscoelasticity of patterned materials often leads to slow response and hysteresis under dynamic stress. Constructing a bionic microstructure on the electrode layer presents an alternative method for enhancing flexible capacitive sensors' performance [19].

3.2. Bio-microstructure resistive mechanism

Piezoresistive tactile sensing operates by detecting mechanical inputs through changes in the electrical resistance of materials. When external stimulation is applied, it deforms both the substrate and the conductive layer, which alters the contact mode between substrates and the distribution of the conductive layer. This process involves brittle yet highly responsive conductive or semi-conductive materials, such as silicon, and results in a change in contact resistance [47]. The common piezoresistive materials are typically prepared by blending nanoparticles and polymers. The piezoresistive effect and the resistance value can be described by specific equations:

$$\frac{\Delta R}{R} = (1 + 2 * \lambda + \pi * E) * \epsilon \quad (4)$$

$$R = \frac{\rho * L}{A} \quad (5)$$

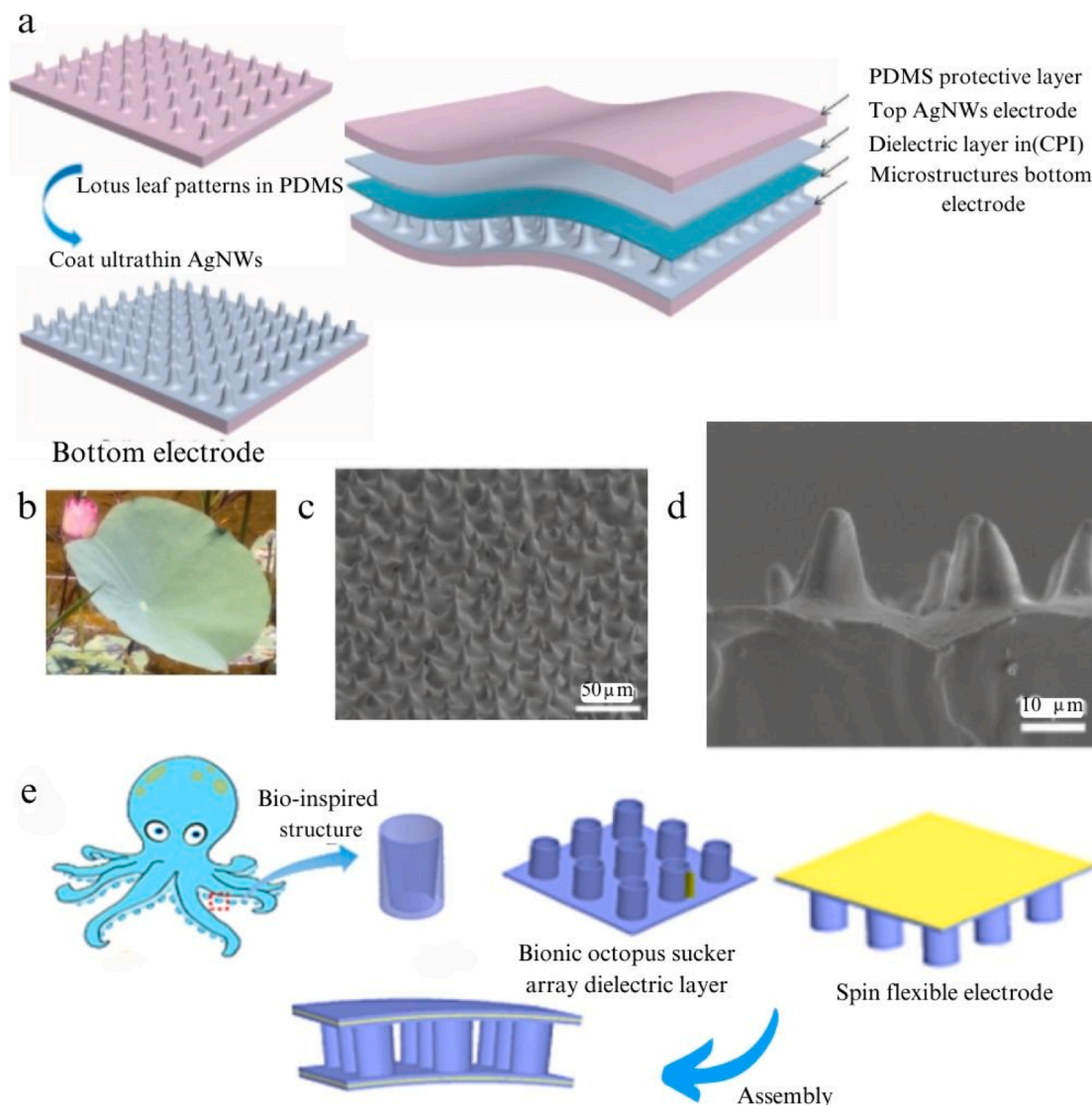


Fig. 5. illustrates various microstructures used to develop flexible capacitive tactile sensors. Panel (a) shows a schematic of a sensor based on the lotus leaf's microstructure, known for its high aspect ratio and sparse design, Adopted [46]. Panel (b) displays a photograph of a lotus leaf, Panel (c) presents a 45° tilt-view SEM image of micro-patterned PDMS (m-PDMS) at a 5 mm scale, and Panel (d) offers a cross-sectional SEM image of 10 mm deep PDMS micro-towers [46]. Panel (e) depicts a diagram of a bionic tactile sensor inspired by octopus' suckers, Adopted [45].

Where R is electrical resistance, ΔR is the change in resistance as a function of applied pressure, ρ is resistivity, λ is Poisson's ratio, π is piezoresistive coefficient, E is Young's modulus, ϵ is longitudinal strain, and L, A are length, and cross-sectional area of the resistor, respectively. Sensitivity, represented as the gauge factor (GF), where (GF) for the strain sensor is defined as:

$$GF = \frac{\Delta R/R_0}{\epsilon} \quad (6)$$

While (GF) for the pressure sensor is defined as:

$$GF = \frac{\Delta R/R_0}{P} \quad (7)$$

where P represents pressure intensity [48]. A constant GF implies a linear relationship between resistance and strain (or pressure), but a fluctuating GF is directly related to the deformation range measured [41]. The piezoresistive sensor exhibits remarkable features such as fast fabrication, high sensitivity, a wide measuring range, and a simple structure. Furthermore, piezoresistive tactile sensors are less prone to

noise, which makes them a better option for array configurations where there is less field interaction or crosstalk between neighboring units [49]. However, its resistance is susceptible to temperature variation, hysteresis is a widespread problem with piezoresistive tactile sensors, which leads to a limited frequency response, and its linear error increases considerably when the sensor undergoes large deformation, thereby its application is restricted by environmental factors [50,51]. For instance, a silicon-based piezoresistive sensor embedded in a soft fingertip showed high-accuracy measurements for both longitudinal and shear stresses [23,24]. Current research in piezoresistive sensors focuses on two main areas. The first is the development of flexible composite sensing materials that demonstrate self-healing properties and exceptional sensitivity to various stimuli [24]. The second area involves constructing micro-structured, flexible sensor devices with enhanced piezoresistive effects using micro and nanoengineering techniques, incorporating both artificially designed and bionic microstructures [52]. These materials include 0D meta nanoparticles, 1D carbon nanotubes (CNTs), and other materials paired with matrix materials such as eco-elastic [53], cotton [54], PDMS [55], and metal nanowires (NW) [56], and 2D materials like MXene and reduced graphene oxide (rGO)

[57,58] polyester [59]. Alternative design approaches, such as crack propagation in thin films and tunneling phenomena, have been explored for their potential to create highly sensitive materials[60,61]. Drawing inspiration from unique biological structures, Fang et al. developed a nanofiber thin film piezoresistive sensor with a pleated structure, leveraging the micro-ridges on the conductive nanofiber's uneven surface to detect human wrist pulse signals Fig. 6 (b)[62].

This method, which changes the contact resistance between neighboring units, shows promise for monitoring small deformations in electronic skin (e-skin), healthcare, and human-computer interface ap-

plications. However, achieving high sensitivity and a wide response range for multi-modal signal detection while maintaining low cost remains challenging. Researchers have turned to replicating biological structures, such as plant leaves and animal organs, to create low-cost, highly sensitive piezoresistive sensors with a wide response range. For example, the microarray-like protrusions on ginkgo leaves make them ideal for low-cost biomimetic microstructure sensors, with secondary structures like wrinkles enhancing sensitivity to small strain stimuli [21, 64]. Liao et al. proposed the heterocontact microstructure (HeCM) to fabricate tactile sensors inspired by the synergistic sensory mechanism

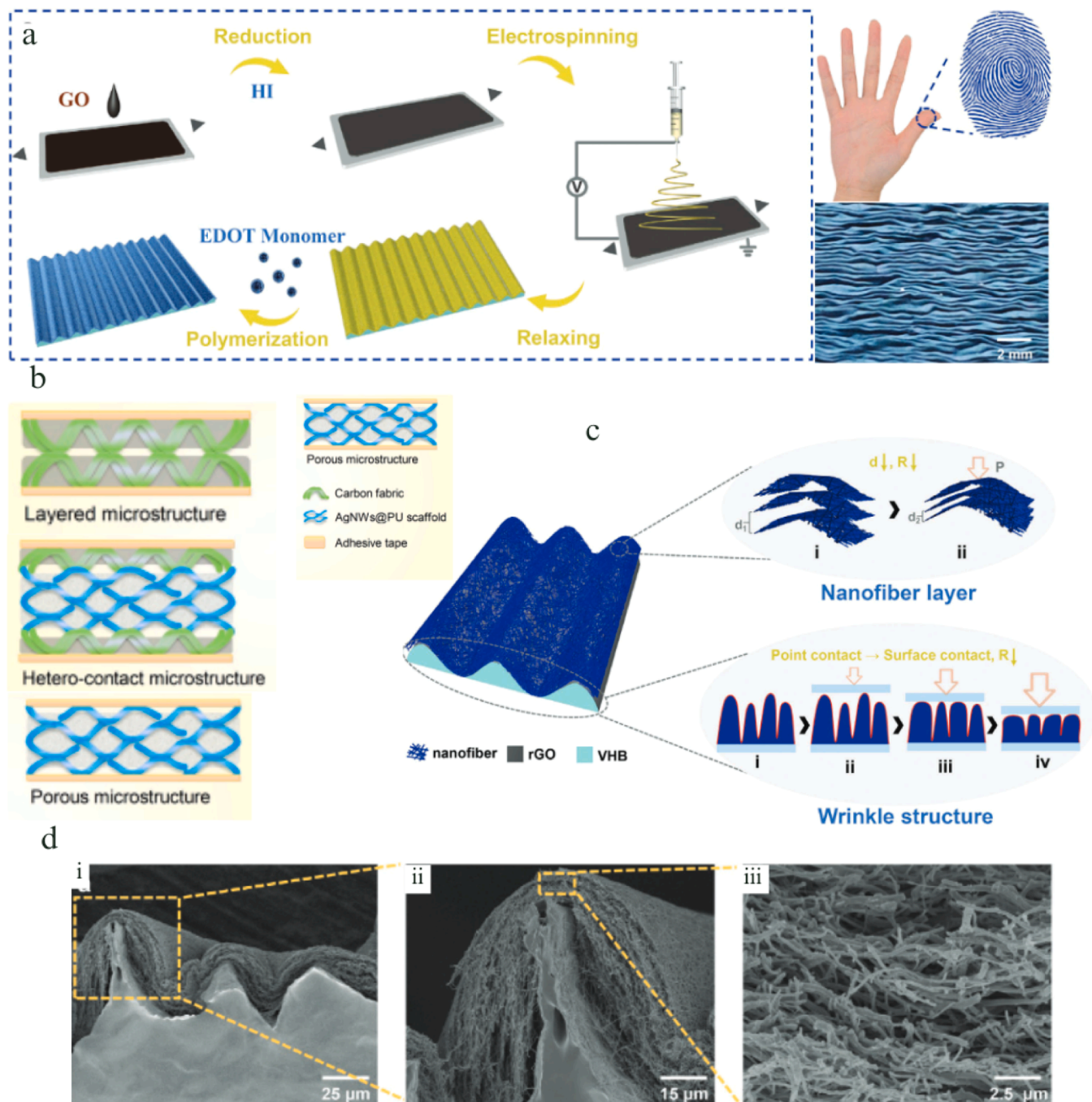


Fig. 6. (a) Preparation Process of 3D PEDOT-Coated Wrinkled Nanofiber Film (PWNF) Active Layer Inspired by Fingerprint Structure; (b) Three types of structural diagrams of tactile sensors based on layered microstructure (LM), porous microstructure (PM), and hetero-contact microstructure (HeCM), respectively [63]. (c) Overall structural schematic diagram of PWNF with VHB substrate, rGO film, and conductive nanofibers, and right view depicting changes in the nanofiber layer and wrinkle structure under external force; (d) Microstructure Morphology and Sensing Mechanism of the Piezoresistive Sensor: (i-iii) Progressive magnification of PWNF cross-sectional structures showing parallel ridge structures, nanofiber film attachment to the elastic substrate, and interlayer structure of nanofibers, **Adopted** [62].

of mammalian tactile mechanoreceptors. The HeCM tactile sensor showed significant enhancements in the Mechan sensational range and sensitivity, with a detection range up to 6.5 N and a 116% increase in range compared to traditional sensors. It also featured fast, stable, and reproducible electromechanical properties, making it ideal for human-machine interactions, virtual reality, and robotics as shown in Fig. 6 (a) [63]. Zhou et al. proposed an interface engineering strategy to fabricate flexible *graphene/Ecoflex* composite strain sensors using a wrinkling mechanism on the Eco flex substrate. This method significantly increased the surface area and interfacial bonding, enhancing strain sensitivity. The sensors demonstrated a high gauge factor (*GF*)

of 1078.1, stretchability up to 650%, durability over 3, 000 cycles, and a response time of about 140 ms. These sensors can detect a wide range of physiological signals, showing significant potential for real-time medical diagnosis and remote assistance in military and industrial applications [21]. Chen developed a conductive microfilm by preparing an aqueous mixture of single-walled carbon nanotubes (SWCNTs) and polyvinylpyrrolidone (PVP), which, after solvent evaporation, resulted in internal dendritic self-assembly structures. Further mixing with MXene produced hierarchical dendritic-lamellar structures Fig. 7 (c-d). The MXene/SWCNT film showed higher flexibility, stronger adhesion, and a hierarchical rough surface. As an electrode layer for a

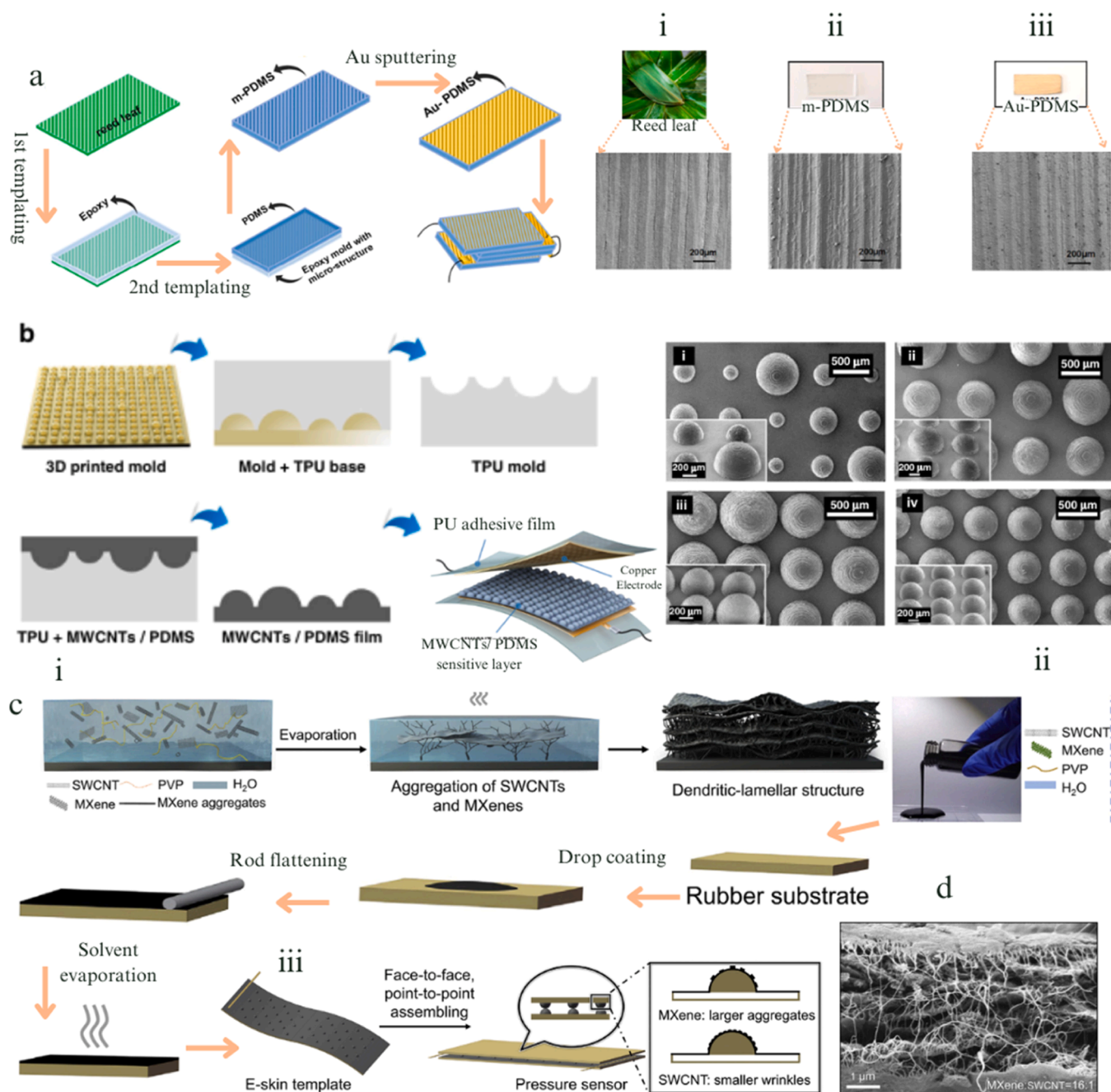


Fig. 7. showcases various methods for creating and characterizing microstructure-based piezoresistive sensors. a) Fabrication of a flexible pressure sensor using photos and SEM images. (i) Reed leaf structure, (ii) m-PDMS, (iii) Au-PDMS [66]. b) Fabrication process for a pressure sensor with a tunable sensitivity MWCNT/PDMS film. It includes a schematic diagram, top-view SEM images, and inset side-view SEM images for sensors with varying target sensitivities [52]. c) Water-induced self-assembly to create a MXene/SWCNT/PVP film for tactile sensors. It shows photos of the ink and a schematic illustrating the film formation process. d) Cross-section of an MXene1.5/SWCNT/PVP film under SEM[65].

piezoresistive sensor, it achieved high sensitivity ($165.35kPa^{-1}$), a low detection limits ($0.69Pa$), a response time of $\sim 48ms$, and good cycling stability over 10,000cycles, making it suitable for voice recognition and pulse sensing. An artificial skin with sensor arrays was also demonstrated [65].

Wang et al. developed a multilayer piezoresistive bio-nanostructured sensor by replicating the one-dimensional microstructure of a reed leaf using PDMS, which enhances sensitivity and enables the recognition of tangential force Fig. 7 (a) [66]. This sensor can detect pressure, deformation, and tangential force, with a response time of 30ms and a wide linear range up to $107kPa$, making it suitable for medical detection and human-machine interaction. Xu et al. introduced a new design strategy for micro-hierarchical structures based on the hyperplastic mechanics of sensitive elastomers as shown in Fig. 7 (b). Their pressure sensors exhibited customizable sensitivity ($0.7, 1.0, \text{ and } 1.3kPa^{-1}$) and high linearity (≈ 0.99) over a working range of about 200 kPa. The sensors also demonstrated fast response/release times (12.5/37.5ms), a low detection limit of $35Pa$, and repeatability for over 10,000cycles [52].

3.3. Bio-microstructure piezoelectric mechanism

Piezoelectric sensors, classified as active sensors, convert mechanical energy into electrical charge through mechanical deformation and the piezoelectric effect as shown in Fig. 8 (a, b) [67]. These sensors are highly sensitive, have a broad frequency bandwidth, a high signal-to-noise ratio, self-powering capabilities, low energy consumption, lightweight properties, and reliable performance, making them ideal for dynamic measurements [68]. An example is a sensitive gait recognition system using an array of piezoelectric flexible sensors to monitor respiratory pulse and muscle behavior accurately as shown in Fig. 8 (d. i, ii, iii) [69]. However, these sensors are best suited for dynamic monitoring and do not provide optimal sensitivity for static medical detection. Piezoelectric tactile sensors utilize passive and active sensing mechanisms. Passive tactile sensing employs the direct piezoelectric effect, where material polarization under external mechanical stress generates electrical charge, as illustrated in Fig. 12(c) [34], and the resulting electrical charge density can be represented as [47].

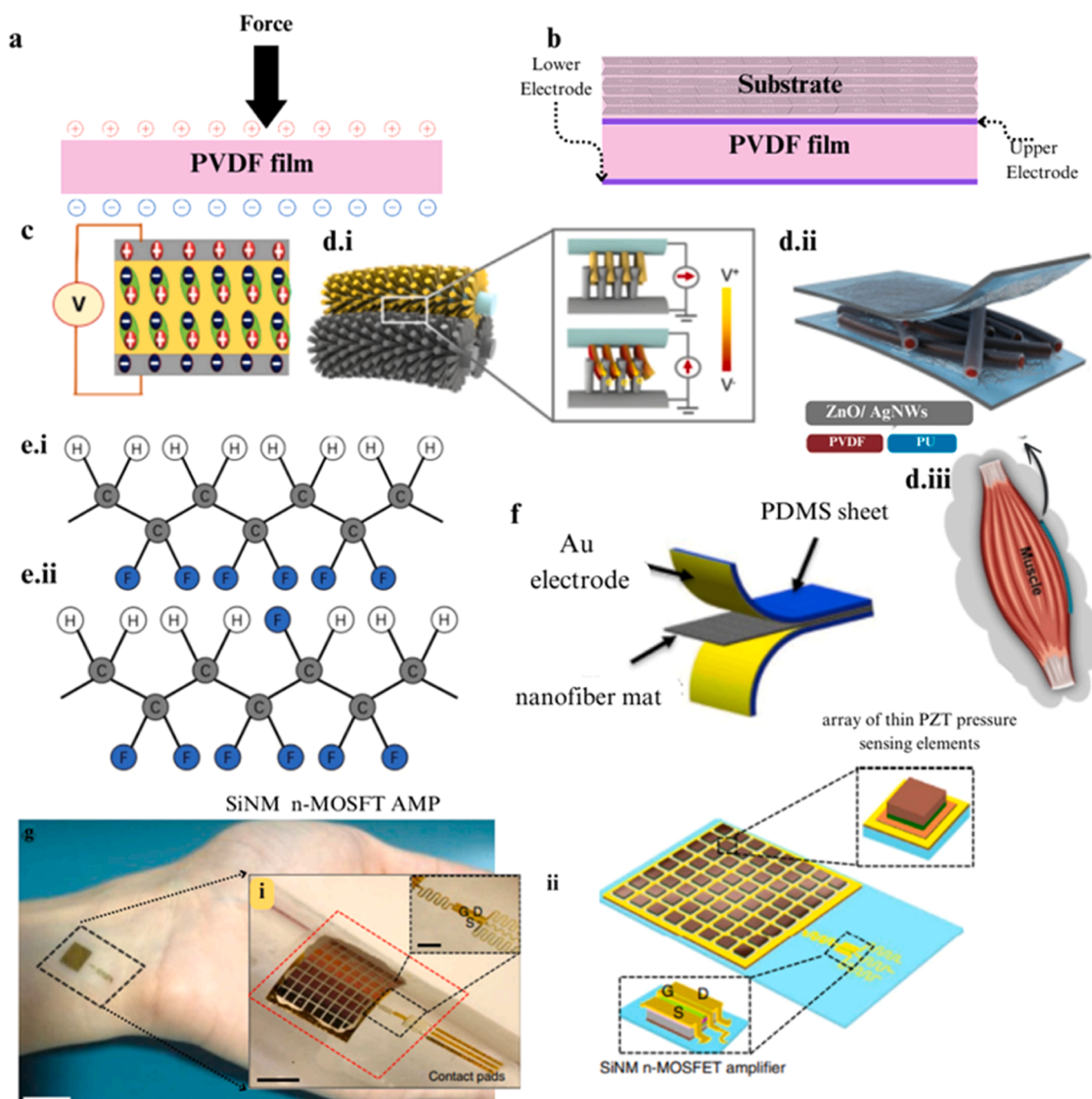


Fig. 8. : (a) Piezo-electric tactile sensor fundamental structure, and (b) schematic PVDF circuit, Adopted [67,102]. (c) Schematic circuit of the Piezo-electric effect, Adopted [34]. (d. i, ii) Schematic illustration of Piezoelectric Potential Generation in Hierarchically Interlocked PVDF/ZnO Fibers-Based PME for Muscle Behavior Monitoring Adopted [69]. (e. i) Schematic diagram of β -phase for the crystal structure and the molecular conformation of the PVDF, and (e. ii) Schematic diagram of conformation VDF-TrFE copolymer molecule in β phase (all-trans (T)), Adopted [72]. (f) Illustrate composite film of PZT-PVDF Adopted [78]. (g. I, ii) provides a schematic circuit of Piezoelectric transducer based on thin film of PZT with scale range of layers between $1.2\mu m/400nm$, Adopted [73].

$$D_i = d_{ijk} * X_{jk} \quad (8)$$

Where the charge density is D_i in the i direction of a Cartesian coordinate system. piezoelectric coefficient denoted by d_{ijk} . X_{jk} represents the externally applied effect that serves as sensing input. Common methods for polarizing PVDF include thermal, stretching, and corona polarization, which align molecular dipole moments along the electric field direction [70]. Compared to resistive and capacitive sensors, piezoelectric flexible sensors offer distinct advantages due to their self-powered properties, eliminating the need for heavy batteries and simplifying the sensing system [71]. Piezoelectric materials are categorized into three classes: inorganic materials (e.g., ceramics and crystals), organic materials (e.g., PVDF), and composites [72]. As variety of piezoelectric

materials employed by Elastic tactile sensors, such as polyvinylidene fluoride (PVDF), zinc oxide (ZnO), and lead zirconate titanate (PZT) [69, 73]. Among these, PVDF composites have attracted considerable attention from researchers due to their noteworthy qualities of high flexibility, affordability, and ease of manufacture [48]. PVDF is notable for its higher sensitivity mechanical-to-electric energy conversion rates, dielectric properties, pyroelectricity, mechanical tensile properties, dynamic mechanical responsiveness, and acoustic resistance near air. Additionally, PVDF's softness, lightweight nature, non-toxicity, exceptional biocompatibility, and impermeability to water and chemicals make it ideal for flexible sensors of various shapes and sizes. It also allows for the easy fabrication of flexible sensors in various sizes and

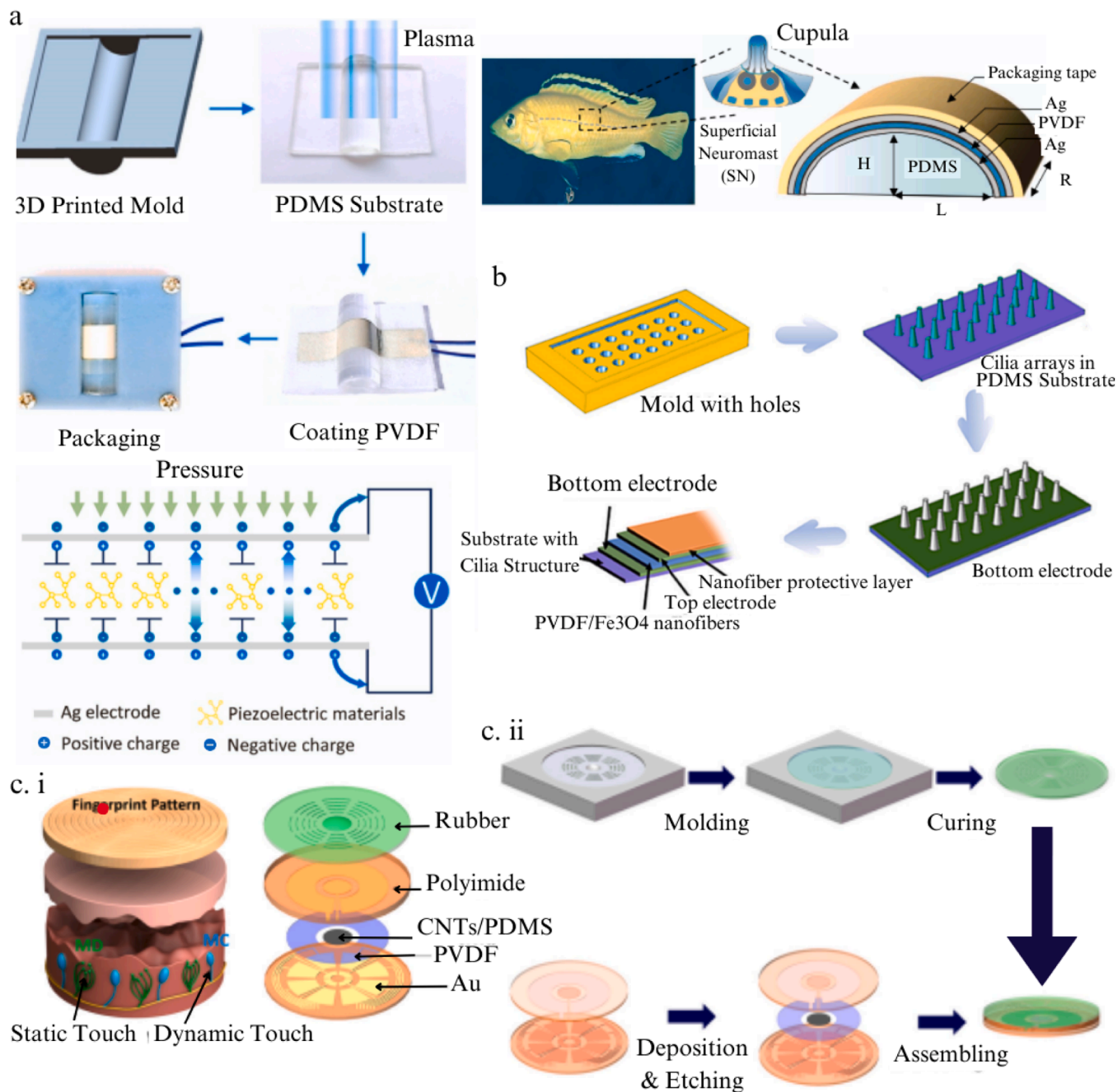


Fig. 9. : Biomimetic Piezoelectric Microstructure Tactile Sensors (a) The fabrication steps and sensing mechanism of a flexible bionic PVDF piezoelectric sensor, Adopted [88]. (b) Schematic illustrating the fabrication of a piezoelectric tactile sensor with cilia-inspired structures, Adopted [89]. (c. i) Diagram of human fingertip skin structure and a fingertip-inspired dual-mode tactile sensor, featuring a fingertip-inspired rubber microstructure layer, two Au-coated PI films, a CNTs/PDMS film, and a PVDF layer. (ii) Schematic showing the fabrication process of the dual-mode tactile sensor, Adopted [90].

shapes due to its low acoustic impedance, offering unparalleled advantages over conventional piezoelectric materials [74,75]. Despite these benefits, PVDF-based sensors have a lower electromechanical coupling coefficient compared to those made from pure ceramics and single-crystal materials. Enhancing this coefficient involves modifying the PVDF material's crystal structure, chemical composition, and crystal orientation. The first includes changing the crystal structure and chemical composition to improve the electromechanical coupling coefficient, such as using piezoelectric single-crystal materials and doped materials. The second strategy focuses on increasing the electromechanical coupling coefficient by modifying the material preparation process, which includes techniques such as high-temperature sintering and stretching [67]. Fig. 8 (g, i, ii) illustrate Inorganic piezoelectric materials like lead zirconate titanate (PZT) and Polycrystalline piezoelectric ceramics, such as BaTiO₃ are known for their toughness and remarkable piezoelectric properties but they have limited applicability due to lead toxicity and the brittleness of polycrystalline ceramics, respectively [76,77]. As a result, they are frequently used as dopants in polymer-piezoelectric ceramic composites. Inorganic piezoelectric materials, such as piezoelectric crystals and ceramics, have stronger piezoelectric coefficients and constants than biological piezoelectric materials but are limited by mechanical properties [78]. Researchers are exploring piezoelectric composites to enhance these properties, recognizing the limitations of single piezoelectric materials. For instance, adding a Tri fluoroethylene (TrFE) group to PVDF results in an all-trans conformation below the Curie point temperature by reducing intermolecular interactions [79,80].

PDMS: polydimethylsiloxane; SWCNTs: single-wall carbon nanotubes; Ag: silver; P(VDF-TrFE): poly (vinylidene fluoride-trifluoroethylene); PVP: polyvinylpyrrolidone; AgNFs: Silver nanofiber. PI: Polyimide; PU: Polyurethane; PEDOT: PSS: poly (3,4-ethylene dioxathiophene) polystyrene sulfonate; Eco flex: Low viscosity, soft, platinum-catalyzed silicone; PVDF: poly (vinylidene fluoride); ITO: Indium tin oxide; PET: Polyethylene terephthalate; ZnO: Zinc oxide; Al: Aluminum, BC: Black Carbon While the copolymer P(VDF-TrFE) demonstrates promising piezoelectric activity, addressing stability concerns remains imperative for further research to overcome phase stability issues. Fig. 8 (e, i, ii) depicts the PVDF and P(VDF-TrFE) conformations [72]. Yuan et al. introduced a biomimetic strategy using PVDF to capture weak force signals with a cylindrical surface, inspired by the lateral line sensing principle of fish [88]. As shown in Fig. 9 (a), the sensor's excellent performance enables it to detect weak forces as low as 0.0005N with a rapid response time of only 4ms, effectively recording breathing motions. This sensor, inspired by the lateral line structure of fish, comprises four components: PDMS, Ag, PVDF, and a magnetic tape protection layer. The convex PDMS substrate provides transparency, stability, and flexibility. The PVDF film reduces interference from industrial frequency signals, and the non-uniform curvature structure enhances stress concentration, improving detection limit and sensitivity. Piezoelectric flexible sensors also have applications in acoustics, particularly in cochlear implants [99,100]. Inspired by the microstructure of human fingerprints, a dual-mode tactile sensor has been developed. As depicted in Fig. 9 (c, i, ii) Xiang et al. integrated capacitive units for static force perception and hybrid nanogenerators for dynamic response. This design features hierarchical wrinkles, enhancing functionality. The capacitive units offer precise three-axis force detection, operating from 97Pa to 210kPa with a sensitivity of up to 45.7%kPa⁻¹, and maintain performance after 5000cycles at 110kPa [90]. The hybrid nanogenerators convert mechanical energy into electricity, efficiently detecting high-frequency vibrations and micro-friction phenomena. Composed of PVDF film and Au-coated PI films, the dynamic unit shows a transient current increase from 20nA to 50nA as compression frequency rises from 1Hz to 10Hz under 30mN loading. This sensor reliably differentiates positions during tapping and sliding, ensuring stable identification of robotic hand movements. The sensor's innovative structure and materials, such as PVDF and PDMS, provide durability and responsiveness,

making it ideal for robotic tactile perception, electronic skins, health monitoring, and environmental evaluation. Its precise perception and adaptation to external stimuli mark a significant advancement in tactile sensor technology. Numerous studies highlight the potential of biomimetic microstructure designs for high-performance sensors. A comprehensive review of tactile sensor microstructures over the past decade emphasizes manufacturing processes and structural characteristics, focusing on enhancing performance for applications in robotics and electronic skins [101].

Traditional hard template methods for replicating plant surface structures limit geometric parameter adjustability and flexible sensor production [103].

The advent of 3D printing technology offers a more suitable approach for producing flexible microstructure sensors, providing advantages like mass production, ease of operation, and personalized customization [104]. Inspired by cilia, Cui et al. proposed a piezoelectric tactile sensor based on a bionic cilia structure via 3D printing technology [89]. The sensor includes a ciliated nanofiber composite electrode of Ag and a nanofiber protective layer, offering distinct advantages over concave-convex or planar structures Fig. 9 (b). The high aspect ratio ciliary structure amplifies nanofiber deformation under external force, improving robustness and output voltage. PVDF enhances the sensor's ability to recognize surface texture and temperature variations due to its thermoelectric and piezoelectric effects. Researchers draw inspiration from nature and combine different microstructures to balance sensitivity, linearity, and hysteresis. Despite progress, challenges remain in creating consistent, cost-effective, and robust microstructures for high-density sensor arrays in harsh environments. Future research should explore advanced process combinations and flexible, multi-functional tactile sensors, including self-healing and biodegradable options. Flexible tactile sensors are highly valued for their sensitivity, flexibility, durability, and compatibility with human skin. Self-powered piezoelectric sensors, particularly those using PVDF, lead the field due to their high sensitivity and energy efficiency, making them ideal for wearable electronics that closely conform to the human body.

3.4. Bio-microstructure triboelectric mechanism

Triboelectric nanogenerators (TENGs) facilitate the triboelectric effect, essential for triboelectric tactile sensors. Initially reported by the Wang research group in 2012 [105]. TENGs operate via contact electrification and electrostatic induction during the interaction of materials with different electronegativities, As depicted in Fig. 10(a), TENGs convert mechanical stimuli into electrical energy, making them promising for energy harvesting applications [106,25]. Common triboelectric sensors function in a vertical contact-separation mode, where pressure induces electron flow and changes the circuit configuration, enabling the detection of static and dynamic tactile signals [26]. Their high output performance, compatibility with flexible designs, stability, lightweight, low cost, ecological harmony, and adaptability to low frequencies have garnered significant interest in energy collection and self-powered sensing applications [107,108,109]. These sensors are frequently used to detect micro-motions of human muscles for human-machine interaction. The selection of contact layer materials is crucial for TENG performance, as triboelectric effects depend on material characteristics and surface roughness [98,110]. Electron-acceptor materials include polytetrafluoroethylene (PTFE), PDMS, polyvinyl chloride (PVC), and electron-donor materials include skin, PU, indium tin oxide (ITO), and cotton significantly impact sensing capabilities [111]. PAN@ZIF-8 nanofibers have emerged as innovative materials with enhanced performance by increasing charge generation during electrification [25]. Despite positive results the of triboelectric nanogenerator's significant application in energy harvesting and smart wearables due to its high-performance energy transition, TENGs face challenges from environmental factors such as moisture, dust, material degradation, temperature dependence, and high voltage-low current output [110,112,

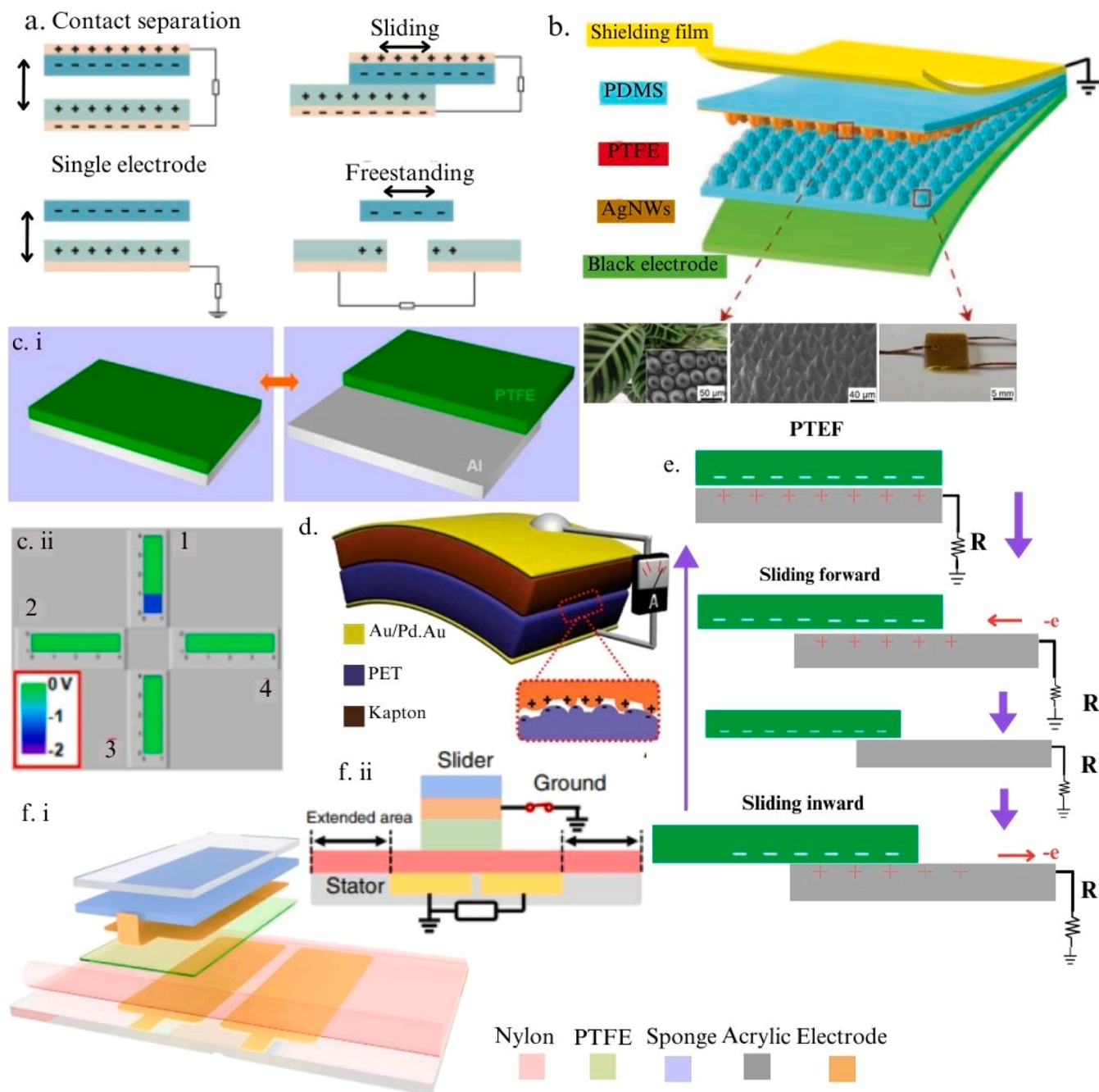


Fig. 10. Illustrate the theoretical model for dielectric-to-dielectric mode: a) Contact-separation, Sliding, Single-electrode, and Freestanding [106]. b) Triboelectric frictional principle-based biomimetic microstructure sensor, including schematic, C. zebrina leaf photograph, micro-morphologies of biomimetic structures and silver nanowires on PDMS, and sensor photograph [115]. c) A schematic diagram of a single-electrode-based sliding triboelectric nanogenerator (TENG) demonstrates output voltages in 16 channels when PTFE contacts the Al strip, as per [119]. d) The structure of an integrated generator in bending process, Adopted [105]. e) Illustrations depict the entire process, electricity generation Adopted [119]. f) The 3D schematic of CSA-S-TENG, including an inset with a cross-sectional view of the extended area structure and grounding electrode, is displayed in (c), and this depiction was adopted from [121].

[113]. Performance enhancements involve selecting appropriate materials and increasing the contact area between films [114]. Wang et al. developed a frictional nanogenerator with a cone-shaped interlocked structure using bionic leaf surface microstructures, significantly enhancing pressure sensitivity Fig. 10(b) [115]. Chen et al. created a flexible device using polyurethane nanofibers (PUNFs) and silver nanofibers (AgNFs) in a PDMS container for moisture protection, ensuring a sensitive response to friction from various angles [116]. Furthermore, composite systems have received a lot of interest in the field of triboelectric nanogenerators (TENGs) because of their ability to

improve output performance. for example, Guo et al. investigated the usage of fluorinated metal-organic frameworks (F-MOFs) as fillers in triboelectric nanogenerators (TENGs) and discovered numerous significant results. F-MOF acts as a bifunctional filler, increasing both charge-trapping and charge-inducing qualities, outperforming typical fillers that just trap charges. Incorporating F-MOF into a polydimethylsiloxane (PDMS) matrix increased output power density to $52\mu Wcm^{-2}$, 11 times greater than TENGs with pure PDMS. [117]. Moreover, F-MOF is compatible with various polymer matrices, not limited to PDMS, indicating its potential for enhancing TENG

performance across different materials. The study identified that the optimal F-MOF mass ratio is 0.5wt%, with higher ratios leading to reduced performance due to aggregation. These TENGs are highly applicable for powering small electronic devices, wearable devices, or underscoring F-MOF's promise in energy harvesting. Additionally, the research opens up new opportunities for functionalizing MOFs, driving further innovation in TENG design and power generation technologies

[118]. Yang et al. have presented a triboelectric device with a single electrode to alleviate signal interference difficulties, replacing the two-electrode method. It is based on relative sliding motion and periodic contact and separation of polytetrafluoroethylene (PTFE) and aluminum layers Fig. 10 (c & e)[119]. This design produces electrostatic and triboelectric effects, allowing charges to travel between the two layers. Furthermore, due to its simple structure and operation principle, a single

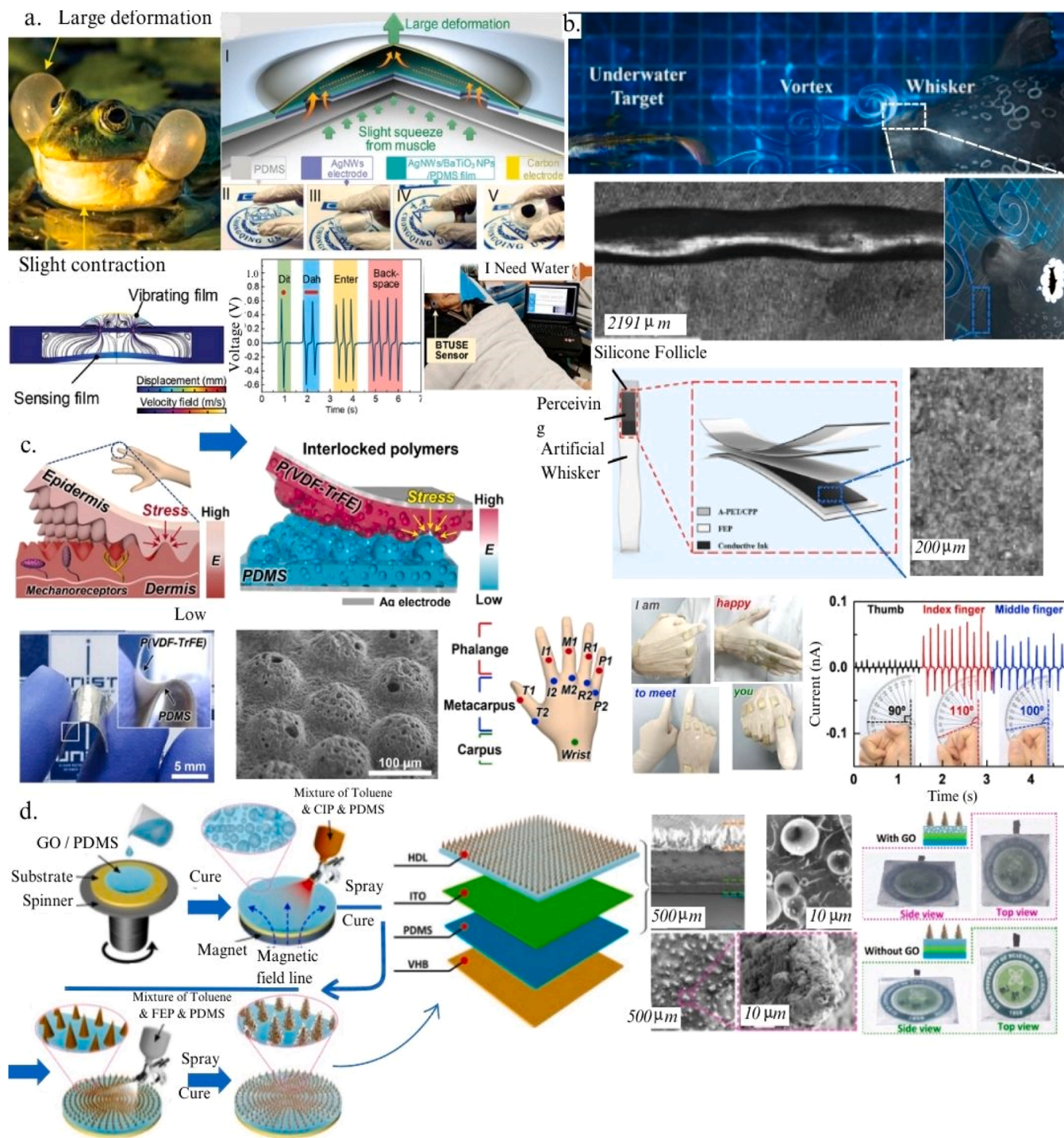


Fig. 11. Biomimetic Triboelectric Microstructure Tactile Sensors include the following innovations: (a) BTUSE Sensor, where frog muscle contractions deform vocal sacs to generate electric signals, depicted through photos and schematics for Morse code-based communication aids in hospitals [94]; (b) Underwater Bionic Whisker Sensor (UBWS), featuring seal-like whiskers that detect fish movements influenced by vortices, illustrated with diagrams and SEM images of whiskers and electrodes [122]; (c) Skin-Inspired Hierarchical Polymer Architectures for Ultrathin TENGs, utilizing nanoporous P(VDF-TrFE) and PDMS micro-ridge structures for flexible smart gloves capable of gesture detection [97]; and (d) Fabrication and Properties of Multimodal HD-TENG, showcasing a superhydrophobic micro-cilia structure through schematic, SEM, and optical images, enhancing sensor sensitivity and functionality, Adopted [26].

electrode-based device can act as a wireless sensor. Ongoing research strives to improve device output performance by modifying electrode materials, surfaces, injecting ions, and controlling the environment [16]. He et al. developed a new sliding mode structure to enlarge the device's charge movement space, hence enhancing the surface density of the electrode Fig. 10 (f). Cao et al. created a self-powered sensor based on crumpled MXene film to detect pressure and strain in wireless human motion [120]. This sensor takes advantage of MXene's conductive qualities, transforming mechanical deformations into electrical impulses through the triboelectric effect. The crumpled structure retains functionality despite various deformations, leading in a broader detection range (0.14 – 22.22kPa) and increased sensitivity.

This construction is adaptable for use in rotating devices that require a high charging output density at low frequencies [121]. Zhou et al. developed a bionic TENG sensor inspired by frog singing behavior, as shown in Fig. 11 (a) [94]. This sensor uses a flexible PDMS elastomer and a deformable membrane to convert vibrations into electrical signals via contact electrification and electrostatic induction. The bionic structure maintains contact separation under small deformations, resulting in a wider detection range (0 – 5mm) and higher sensitivity (54.6mVmm⁻¹). Additionally, Cao et al. created a self-powered sensor based on crumpled MXene film to detect pressure and strain in wireless human motion [120]. This sensor takes advantage of MXene's conductive qualities, transforming mechanical deformations into electrical impulses through the triboelectric effect. The crumpled structure retains functionality despite various deformations, leading in a broader detection range (0.14 – 22.22kPa) and increased sensitivity. Similarly, Inspired by the sensory capabilities of seals, Wang et al. created a bionic whisker sensor to amplify weak external stimuli, distinguishing forces as low as 1.129μN Fig. 11 (b) [122]. This sensor features a flexible structure for capturing complex aquatic stimuli. Similarly, a multi-layer triboelectric sensor with a bionic fin structure was developed for high-efficiency energy collection from various directional water flows, offering potential for underwater detection and sensing. Inspired by the gradient stiffness and interlocked micro-ridge structures of human skin, Ha et al. fabricated and developed a hierarchical nanoporous polymers with gradient stiffness for ultrathin, highly sensitive triboelectric sensors (TESs) [97]. These sensors effectively transmit stress, enhancing compressibility and contact area, enabling detection of vital signs and voice frequencies, and perform well in various environments. As depicts in Fig. 11 (c), This innovative design offers potential applications in next-generation wearable electronics, biometric security systems, human-machine interfaces, and communication devices for the speech- and hearing-impaired. Additionally, Zhang et al. improved moisture resistance by designing a super-hydrophobic dielectric layer with nano-pore structures and bionic petiole-like nano structures [98]. This layer maintains excellent electrical properties and stability under humid conditions. To address challenges in water-containing environments, researchers optimized the dielectric layer's structure by combining bionics to create a waterproof mixed dielectric layer with internal micro-nano pores and graded super-hydrophobic micro-cilia, inspired by human epidermis Fig. 11 (d) [26]. This flexible friction sensor exhibits high flexibility, washing resistance, scalability, and moisture resistance, making it suitable for collecting water droplets and wave energy. It provides new possibilities for self-powered human activity monitoring and blue energy collection. Triboelectric nanogenerators have significantly advanced blue energy collection but face wear issues during continuous high-intensity work, reducing output power and lifespan [123,124].

Du et al. addressed this by designing bionic fish scales to minimize wear between contact layers, achieving one million continuous operation cycles without voltage attenuation [125]. This innovative design demonstrates TENGs' feasibility as a power supply for self-powered electronic devices and large-scale power generation.

4. Application

Biomimetic microstructure flexible tactile sensors, renowned for their ability to mimic human skin, are significantly advancing intelligent microsystems due to their superior characteristics. As a cross-domain technology, they are widely applicable in the development of high-sensitivity, low-cost multifunctional e-skins for healthcare devices, medical diagnostics, human-machine interaction, and minimally invasive surgery (MIS) [126,127]. In medical diagnostics, these sensors are capable of detecting vital signs such as heart rate, blood pressure, and respiratory rate, thereby enabling continuous and non-invasive health monitoring, which in turn enhances patient comfort [128,129]. In the context of human-machine interaction, these sensors have the potential to revolutionize wearable electronic devices and soft robotics by converting human movement signals into control inputs for devices such as gaming controllers or prosthetic limbs, thereby enhancing the user experience. Soft robots equipped with these sensors can interact more safely with humans, leading to significant advancements in rehabilitation and eldercare [130,131,132]. Furthermore, the development of electronic signature systems facilitated by these sensors ensures secure data collection and management [133]. Research on electronic skin is pivotal for the creation of more intelligent robots and for making substantial progress in medical treatments.

4.1. Biomedical Field: exercise monitoring integrating wearable and implantable technologies

The growing adoption of intelligent terminals underscores the significant market potential for wearable electronics. Central to electronic skin technology, flexible tactile sensors can adhere to the human body and monitor crucial physiological parameters, including heartbeat, pulse, blood pressure, and body temperature, in real-time [134]. Achieving flexible and stretchable electronic skin typically involves using elastic substrates or island-bridge structures [135,136]. Various bionic structural designs, tailored to different working principles, enhance the customization and optimization of these sensors. The microstructure of the elastic substrate imparts ultra-compressibility to the pressure-sensitive sensor, which performs well in monitoring large-scale human movements like elbow and wrist actions, maintaining high sensitivity and rapid response with consistent peak intensity [137].

Carbon-based aerogels are favored for their unique three-dimensional network structure, which provides substantial deformation capacity and plasticity. However, their application in sports health monitoring is constrained by their poor mechanical properties and fatigue resistance during cyclic loading [140]. Healthcare monitoring applications, such as electronic skin (e-skin), require higher sensitivity compared to other applications, thus favoring piezoresistive and piezo-capacitive effects over piezoelectric and triboelectric principles. Nevertheless, devices utilizing piezoresistive and piezo-capacitive effects frequently encounter a low signal-to-noise ratio (SNR) [141]. Piezoresistive pressure sensors, which consist of flexible substrate electrodes and active pressure-sensitive materials, have seen notable advancements, particularly with carbon nanomaterial-based materials that are both cost-effective and environmentally friendly [57]. To overcome this limitation, the 3D carbon-based tactile foam sensor demonstrates high stretching properties, enhanced SNR, and robust deformation resistance to external stimuli. Biomimetic designs inspired by leaves, which are highly sensitive to environmental changes, are particularly effective [141]. For example, Nie et al. replicated the layered microstructure of banana leaves to develop sensing electrodes for pressure-sensitive sensors, allowing effective monitoring of physiological signals such as breathing and wrist pulse Fig. 12(a) [138]. Similarly, Tang et al. utilized the bionic structure of oleander leaves to create flexible sensors capable of detecting subtle fitness movements Fig. 12(b) [139]. Capacitive sensors, noted for their fast dynamic response, are frequently used in medical applications to monitor patient

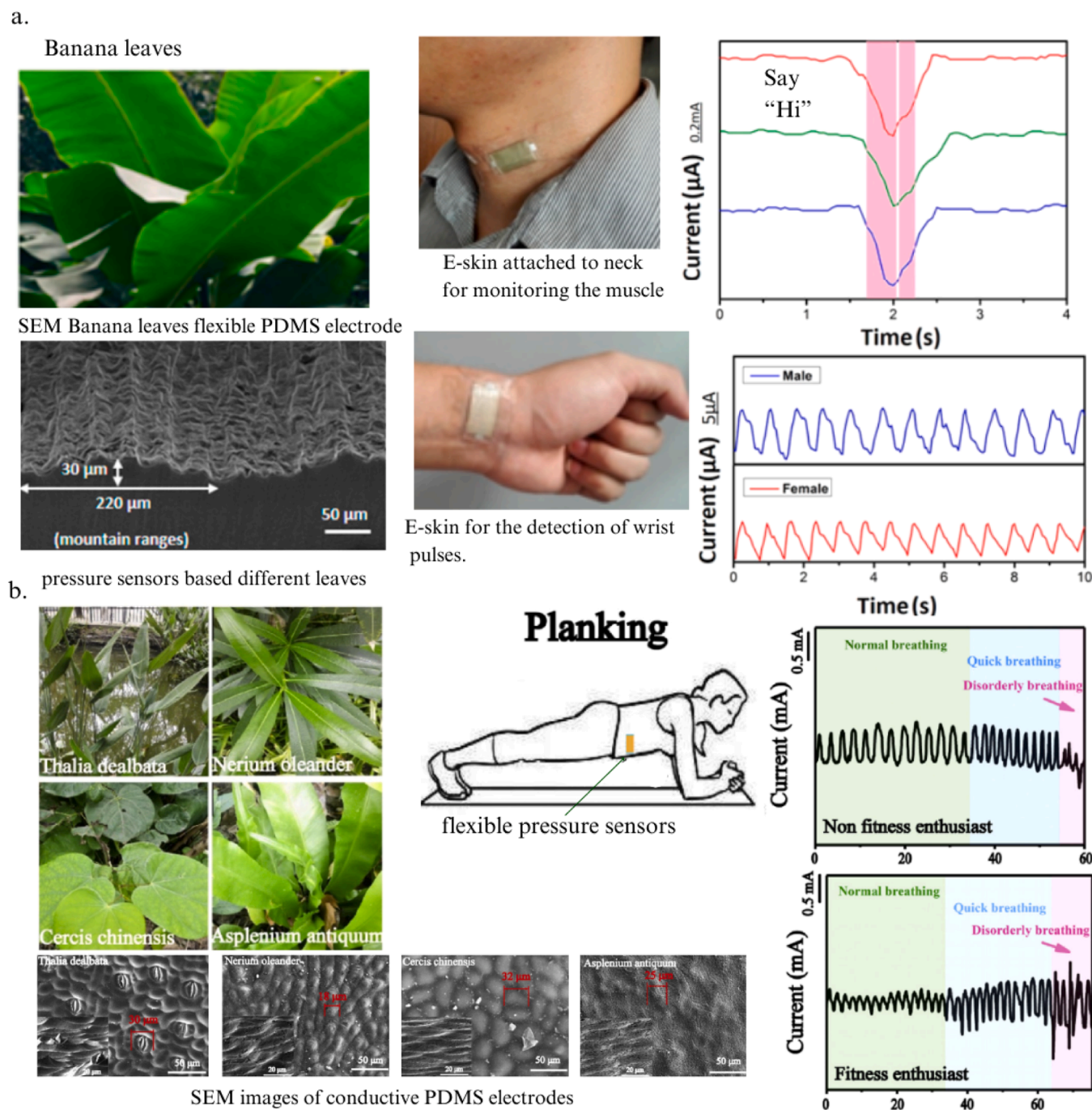


Fig. 12. (a) Shows the application of flexible PDMS-based pressure sensors, including cross-sectional views of micropatterned electrodes and their use in monitoring muscle movements and wrist pulses, with real-time $I - t$ curves [138]. (b) Presents bioinspired flexible pressure sensors modeled after plant leaf microstructures, with SEM images and a comparison of breathing patterns during planking between fit and unfit individuals [139].

behaviors, such as finger flexion and fist clenching [142]. Lin et al. developed a versatile biomimetic cellulose nanocomposite hydrogel through dynamic borate ester bond crosslinking between Ag/TA@CNC nanohybrids and PVA chains. This hydrogel features exceptional stretchability, rapid self-healing, adhesiveness, antibacterial properties, and mechano-stimuli sensitivity, enhancing its 3D conductive network and achieving an electrical conductivity of 4.61 S/m. It also demonstrates 98.6 % self-healing efficiency within 10 min and exhibits significant antibacterial efficacy Fig. 13(b). The hydrogel effectively detects complex body motions, facial expressions, speech, and respiration, highlighting its potential for advanced self-healing, wearable, and flexible bio-devices [143]. Piezoelectric and triboelectric sensors,

recognized for their self-powered capabilities, are increasingly utilized for continuous dynamic monitoring, particularly in healthcare.

Pu et al. proposed an ultra-stretchable, transparent, and soft triboelectric electronic skin designed for biomechanical energy harvesting and tactile sensing [145]. This electronic skin, using elastomer and ionic hydrogel as the electrification layer and electrode, achieves high transparency and stretchability, scavenging human motion energy and displaying pressure sensitivity of 0.013 mV kPa⁻¹. A 3 × 3-pixel artificial skin was demonstrated to detect touch position and pressure. Wang and Li made efforts to prepare biomedical devices that could be implanted into the body. Thus, they created a flexible, miniaturized, self-powered endocardial pressure sensor (SEPS) based on TENG, which

a. Photograph of the SEPS SEM image of a nanostructure on the PTFE b.

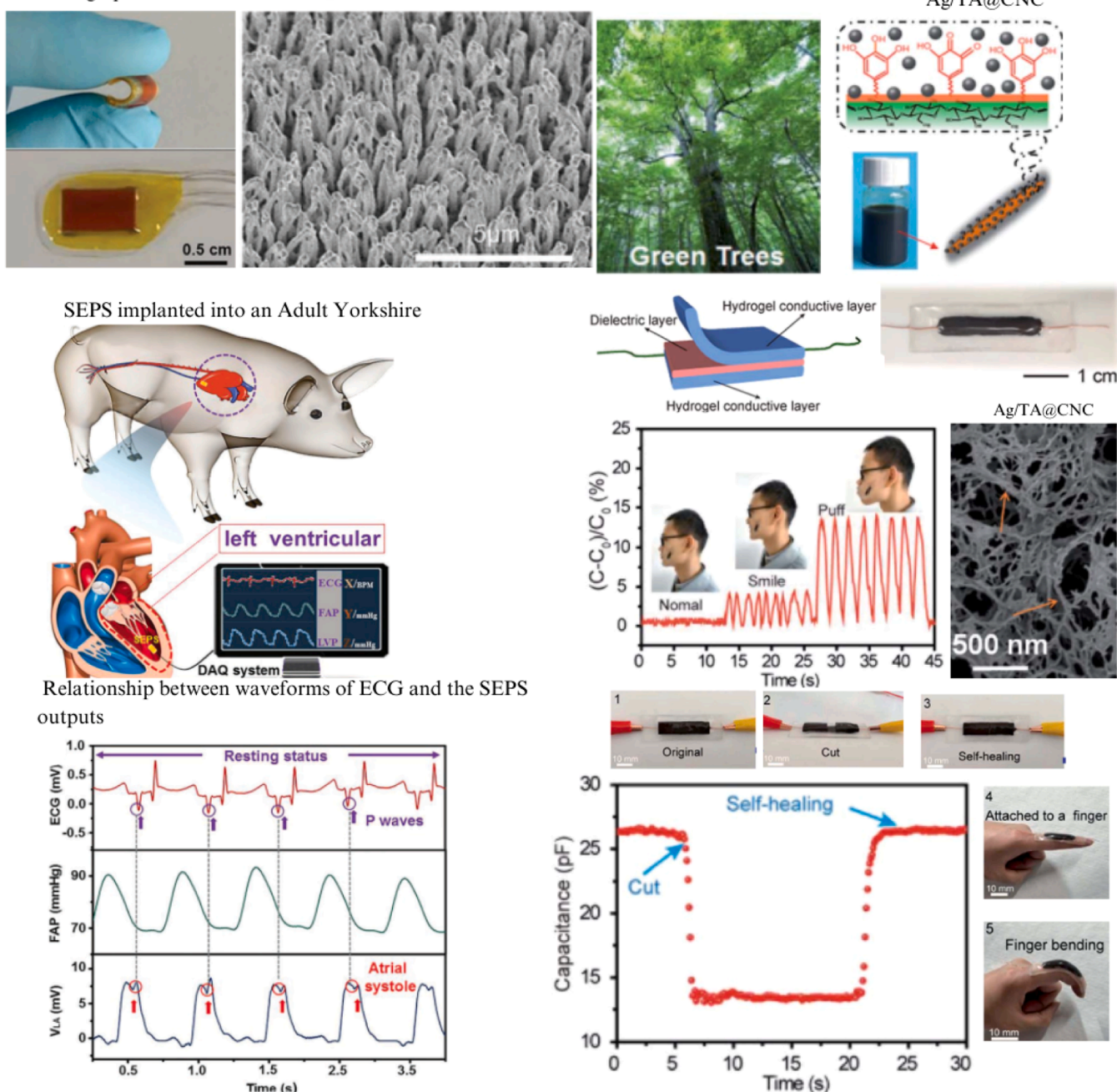


Fig. 13. (a) Shows the SEPS in different states, including SEM imaging and a schematic of its implantation in a swine's heart, with an analysis of ECG and SEPS output correlation [144]. (b) Depicts the chemical structures and construction of TA@CNCs, the microstructure of the PB-Ag/TA@CNC hydrogel, and its application as a capacitance sensor, including self-healing performance and motion detection [143].

is minimally invasive and implanted using surgical catheters. This sensor exhibits high sensitivity to small changes in endocardial pressure across various states Fig. 13(a) [144]. The miniature SEPS, integrated with a PVC retractable catheter for minimally invasive implantation, was analyzed alongside ECG and FAP signals in various states. In the resting state, the device showed minimal impact on cardiac function stability. During activity, the SEPS responded accurately to endocardial pressure, with output peaks showing slight fluctuations aligned with the systolic FAP, indicating consistently high endocardial pressure. The device also demonstrated high sensitivity to minor pressure changes. Kim et al. introduced a flexible reading integrated circuit that combines piezoresistive, piezoelectric, and pyroelectric effects using graphene and

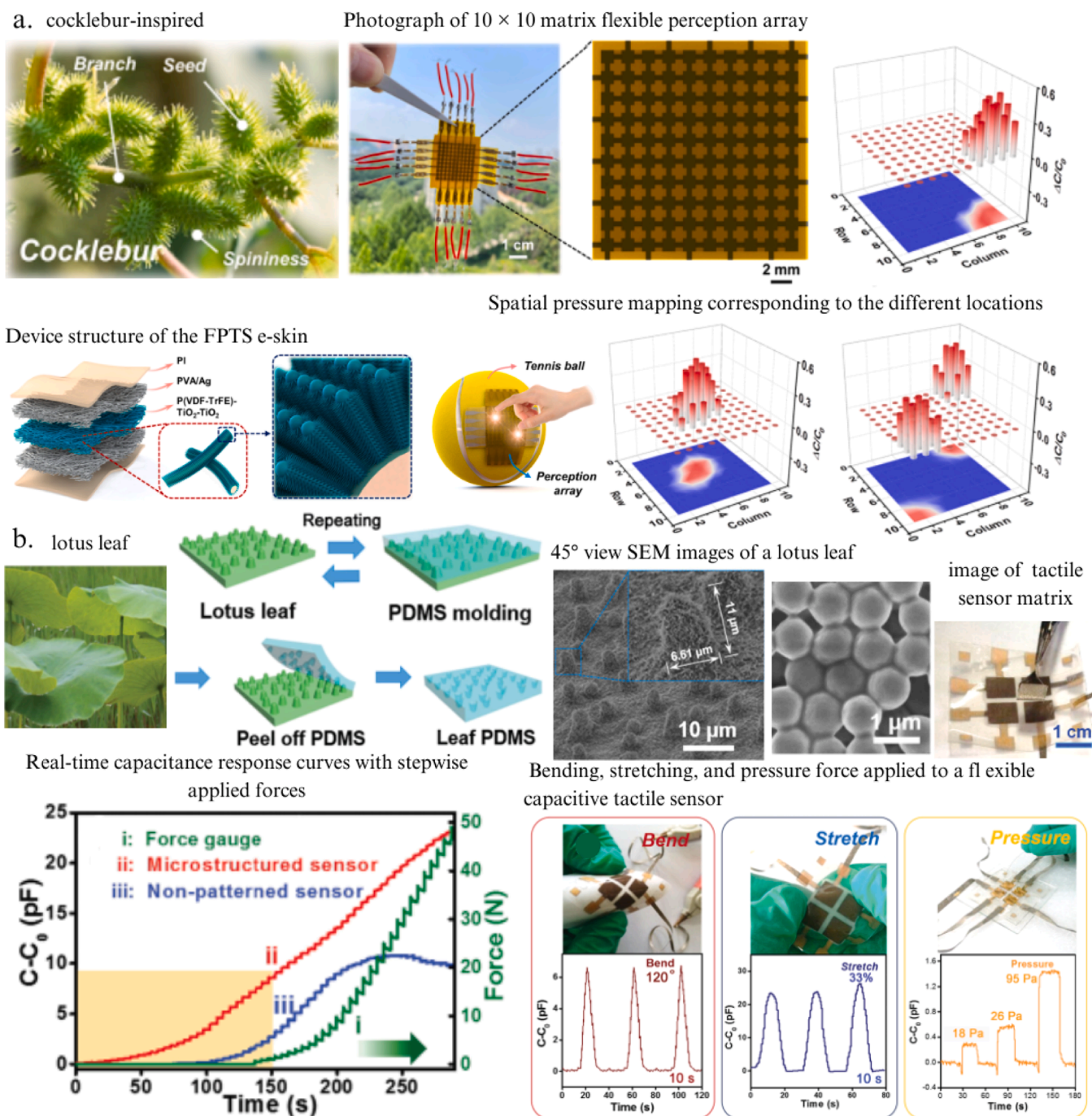
PVDF as the substrate [146]. This flexible module operates by selecting an appropriate mode for the specific body part to obtain the desired signal, thereby enhancing the device's adaptability for various health-care monitoring applications. The advancement of flexible and stretchable sensors, driven by innovative designs and materials, offers promising applications in real-time physiological monitoring and self-healing wearable electronics, paving the way for more sophisticated and integrated health-monitoring solutions.

4.2. Multifunctional Artificial skin for enhanced human-machine interaction and intelligent robots

The ongoing advancements in scientific technology have ushered human life into a new era of intelligence, where everyday products and production devices are interconnected through sensors and actuators. These components enable intelligent recognition and management by collecting, processing, and analyzing diverse data [147,148]. Mechanosensory electronic skins (e-skins) are pivotal in human-machine interaction applications, serving as a crucial interface between humans and machines. Comprising mechanical and stretchable sensor networks, e-skins have demonstrated significant value in various

applications, including robotics [149,150], health monitoring devices [151], and prosthetics [152,153], relying heavily on the ability to perceive diverse signals [154]. To develop multifunctional e-skins capable of high perception across a range of static and dynamic stimuli, integrating numerous macroscopic sensing elements onto thin, flexible tactile substrates is essential [155].

The progress in information technology has also catalyzed a "tactile revolution" in various service facilities integral to daily life, such as mobile phones, computers, household appliances, and media carriers for entertainment and education [158]. Consequently, tactile sensors have become core devices for enabling intelligent perception in robots. For instance, Niu et al. designed a 3D layered resistive pressure sensor



inspired by the cocklebur, comprising branches, seeds, and spines Fig. 14(a) [156]. This sensor was applied to robot fingers to detect pressure at different positions, achieving Chinese medicine pulse diagnosis of the radial artery and recognizing spatial pressure on flat/curved surfaces and Braille characters, which is significant for developing intelligent sign language translation in AI. Natural structures offer excellent models for responsive sensors. Li et al. mimicked insect hair

structures using spinal nanostructured zinc oxide fine particles, resulting in devices with fast response times, high sensitivity, and excellent mechanical resilience [159,160]. Capacitive pressure sensors, noted for high stability and low hysteresis, have great potential in human-machine interaction. Inspired by lotus leaves, Li et al. developed a micropatterned substrate for tactile sensors, combining polystyrene microparticles to form a sensor highly sensitive to bending, stretching,

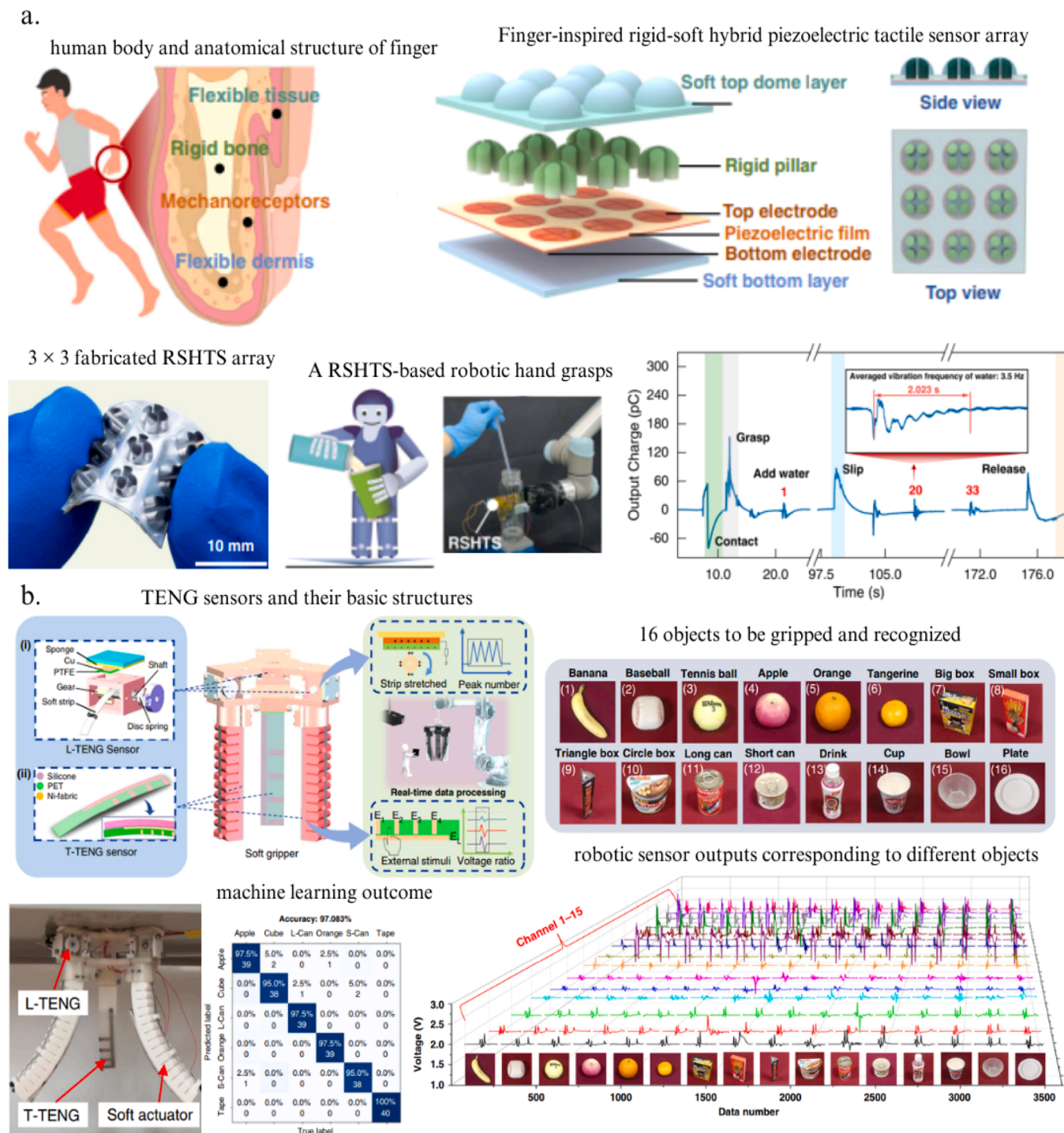


Fig. 15. (a) Depicts the concept and structure of the RSHTS, including a finger-inspired piezoelectric tactile sensor array, a 3 × 3 RSHTS array in action, and its application in robotic grasping with water vibration analysis [162]. (b) Shows the design and application of low-cost TENG sensors for soft grippers, including the TENG sensor types (L-TENG and T-TENG), integration into a soft gripper, and the sensory data processing strategies with machine learning outcomes for object recognition [163]. In speech-controlled human-computer interaction, Guo et al. developed a wireless piezoelectric flexible sensor for the throat to recognize muscle movements, showing potential for speech recognition and intelligent human-computer interaction [164]. The combination of tactile sensors with advanced analysis systems can yield remarkable results, positioning them as outstanding candidates for development in various applications.

and pressure Fig. 14(b) [157]. Zhao et al. further enhanced this design, creating a flexible sensor array with micro-convex structures that accurately measure different pressures based on capacitance changes [161]. In AI and robotics applications, piezoelectric sensors have gained significant interest for human-computer interaction interfaces and robotic dynamic sensing. Zhang et al. designed a biomimetic piezoelectric tactile sensor inspired by human fingers, capable of detecting multiple force directions and demonstrating high operational flexibility in robotics Fig. 15(a) [162]. For soft robots, monitoring proprioception is challenging due to their deformable nature. An intelligent soft robot gripper system based on TENG sensors has been developed to capture continuous motion and tactile information, successfully recognizing various objects with high accuracy Fig. 15(b) [163]. These sensors, integrated into soft robot grippers, enhance their capability to detect sliding, contact positions, and bending angles, paving the way for their application in intelligent factory management and unmanned warehouses. Liquid and bioinspired materials are increasingly used for their high deformability and good electrical conductivity.

Conclusion

The development of electronic skin (e-skin) technology has significantly progressed from its origins in fiction to real-world applications, driven by advancements in microelectronics and material science. Modern e-skin designs incorporate biomimetic microstructures like pyramids, domes, and nanofibers to enhance sensor performance in terms of sensitivity, flexibility, and durability. Self-powered sensors using piezoelectric materials like polyvinylidene difluoride (PVDF) and zinc oxide (ZnO), along with multi-mode e-skins integrating capacitive and piezoelectric sensors, stretchable electrodes, and self-healing materials, exemplify these advancements. This review provides a comprehensive analysis of recent developments in e-skin technology from 2018 to 2023, emphasizing the role of biomimetic microstructures in improving tactile sensor capabilities and discussing functionalities such as freeze resistance, corrosion resistance, self-cleaning, and degradability. To summarize, e-skin technologies have improved through a variety of sensing techniques. Capacitive sensors, which are commonly employed in human-machine interfaces, have excellent sensitivity and resolution, but they are susceptible to interference from external fields. Piezoresistive sensors have large detection ranges, however they suffer from hysteresis in dynamic settings. Piezoelectric and triboelectric e-skins, particularly self-powered variants, are excellent for dynamic applications such as muscle movement monitoring and energy harvesting; nevertheless, stability and long-term durability must be enhanced. Despite these limitations, incorporating biomimetic architecture and novel materials has moved e-skins closer to resembling human skin in healthcare and robotics. Looking ahead, the future of e-skin technology promises further advancements through the exploration of more complex biomimetic structures, integration of artificial intelligence (AI) for enhanced human-machine interfaces, and the development of self-sufficient energy systems. Additionally, efforts to improve the durability, biocompatibility, and miniaturization of sensors will expand their application potential, particularly in wearable health monitors and medical devices. Cross-disciplinary collaborations between materials science, biomedical engineering, and AI will be crucial in accelerating the development of multifunctional e-skins that can replicate human-like tactile sensing with unprecedented functionality and adaptability. Ultimately, continued innovation in this field will bring e-skins closer to achieving the goal of truly human-like sensing in artificial systems.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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