Received: 14 January 2022 | Revised: 9 March 2022 | Accepted: 21 March 2022

DOI: 10.1002/eom2.12209

EcoMat FUNCTIONAL MATERIALS FOR GREEN ENERGY AND ENVIRONMENT WILEY

REVIEW

Bioinspired sensor system for health care and human-machine interaction

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Funding information

National Natural Science Foundation of China, Grant/Award Numbers: 61875015, T2125003; Natural Science Foundation of Beijing Municipality, Grant/Award Number: JQ20038; Strategic Priority Research Program of Chinese Academy of Sciences, Grant/Award Number: XDA16021101

Abstract

Bioinspired sensor system leads the development of new generation sensor technology with remarkable features like ultra-sensitivity, low-power consumption and self-adaptability. With the help of bioinspired sensor systems, human perception can be quantified and machines can be endowed with specific perception. As an emerging technology, bioinspired sensor system has been widely used in various fields such as industrial, medical, food safety, military and robotic. This review summarizes the recent process of bioinspired sensor system. First, three bionic strategies are defined as bionic materials, bionic structures, and functional bionic according to the sources of bionic inspiration. Second, bioinspired sensor systems with different working mechanisms are summarized and classified into piezoresistive, capacitive, triboelectric, piezoelectric, and other types. Afterward, for applications, the representative works of bioinspired sensor system for health care and human-machine interaction are focused and introduced, respectively. Finally, the current challenges and prospects of bioinspired sensor system are also discussed.

KEYWORDS

bioinspired, health care, human-machine interaction, sensor system

1 | INTRODUCTION

Sensor systems can detect changes in the environment and provide feedback on the signals they detect. The goal of sensor systems' development is to improve the functional linkages between "perception" and "feedback," including high sensitivity and response rate, low-power consumption, reliability, miniaturization, intelligence,

Jiangtao Xue and Yang Zou contributed equally to this work adaptivity, and anti-interference capability. Learning from nature is the most efficient approach to solve existing problems in architectural, industrial, medical, and other fields.[1] In the long process of evolution and natural selection, natural sensory systems have evolved distinctive materials and well-adapted structures from the cellular to the organ level. Numerous natural sensory systems of organisms work in unique ways and exhibit impressive performance, which provides rich inspiration for artificial sensor systems. Bioinspired sensor systems, in comparison to traditional sensing systems, use existing technologies and processes to simulate natural structures and materials, resulting in performance that is comparable to natural sensing systems. In addition to the performance of high sensitivity, rapid response, durability, and low-power consumption, it also gives the sensing system some specific properties, such as self-healing, self-cleaning, adaptability, and so on. As a result, bioinspired sensor systems have emerged as a hot research direction in recent decades, combing biology, physics, chemistry, material science, electrical engineering, computer science, and other disciplines. The development of bioinspired sensor system has been greatly advanced by the diversity and resourcefulness of natural sensory systems and the multidisciplinary intersection.

The bioinspired sensor system aims to realize a closed-loop of "perception" and "feedback" in practical applications by imitating natural sensory systems. There are three bionic strategies for bioinspired sensor systems, including bionic materials, bionic structures, and functional bionic. Constructing bionic materials is an approach to endowing traditional materials with novel properties by mimicking organisms' natural materials. For example, responsive photonic crystals materials inspired by chameleons can change color by changing the periodic micro/nanostructure.[2] In nature, whether plants or animals, some unique tissue structures play vital roles in life activities, which provide essential guidance for designing artificial sensors. Designing bionic structures aims to mimic specific biological structures in nature to improve the performance of existing sensors or endow sensors with new functions. The adaptive tendril coiling structure of climbing plants and the interlocking structure of human skin, for example, have long inspired artificial actuation and sensing systems.[3,4] The functional bioinspired sensor system is designed to achieve the same functions and features as specific natural sensory systems, which can be realized by imitating biological materials and structures or other technical means after understanding biological processes. According to different working principles of sensors, here we divide bioinspired sensor systems into piezoresistive type, capacitive type, triboelectric type, piezoelectric type, and other types. Each type of bioinspired sensor system has its unique sensing characteristics, which will be introduced in the following subsections.

Bioinspired sensor systems can broaden the range of human perception and endow machines with specific sensory ability.[5] Physical (sound, light, heat, humidity, etc.), chemical (pH, ion concentration, etc.) and biological (glucose, protein, RNA, etc.) information can all be gathered from the environment or organism itself through bioinspired sensor system. Bioinspired sensor system has been successfully applied in many fields such as biomedicine, human-machine interaction, environmental monitoring, food safety due to its efficient sensing properties. For example, the bioinspired sensor implanted into a prosthesis can establish a link between the human body and the prosthesis, conferring the possibility of manipulating and feeling the prosthesis.[6] Electronic nose[7] or electronic tongue[8] can detect and identify the composition of the surrounding environment or food rapidly. Tactile sensors[9,10] with bionic characteristics can be utilized in human-machine interaction and intelligent robots. Some flexible wearable bioinspired sensor systems[11] can be used to analyze human body fluids quickly and effectively. Artificial synapses[12] and artificial nervous systems[13,14] are used in human-machine interfaces to achieve the conversion between biological signals and electronic signals. Electronic skin[15] with multiple sensing modes will endow robots with the same sensation as humans. Some reviews have been published recently that cover various elements of bioinspired sensors focused on signal receptors, and related bioinspired sensing systems are classified from the point of view of five traditional senses.[16,17] In terms of applications, Xiao et al.[18] described the representative work of bioinspired sensor systems in ion transport, while Li et al.[19] summarized bionic sensor systems' use in the field of prosthetic interface. In this review, we focus on the applications of bioinspired sensor system for health care and human-machine interaction, which affect people's lives in all aspects. We have summarized the latest research progress of bioinspired sensing systems, as well as forecasted future developments. First, according to the sources of bionic inspiration, the bioinspired sensor system is separated into three categories by bionic strategies, which are described as bionic materials, bionic structures, and functional bionic. Second, the bioinspired sensor systems with different working mechanisms are summarized and classified into piezoresistive, capacitive, triboelectric, piezoelectric, and other types. Afterwards, for applications, the representative works with special functions constructed based on meaningful and interesting bionic ideas are introduced. Finally, the current challenges and prospects of bioinspired sensor systems are also discussed.

2 | BIONIC STRATEGIES OF BIOINSPIRED SENSOR SYSTEM

Bionics studies link biological materials, structures, functions, and biomechanisms found in nature with current technology, with wisdom transferring from nature to human technologies.[20] The bionic strategies of bioinspired sensor systems are take inspiration through living organisms from nature to enhance the performance of existing sensors, endow sensor systems with new functions, or develop new sensing methods, which can be generally divided into three categories: bionic materials, bionic structures, and functional bionics, as illustrated in Figure 1. Based on these three bionic strategies, researchers have attempted to develop bioinspired sensor systems that rival the performance of natural sensory systems.

2.1 | Bionic materials

Bionic materials are materials developed inspired by the components, unique characteristic properties of natural biological materials.[29] There is a wide range of bionic

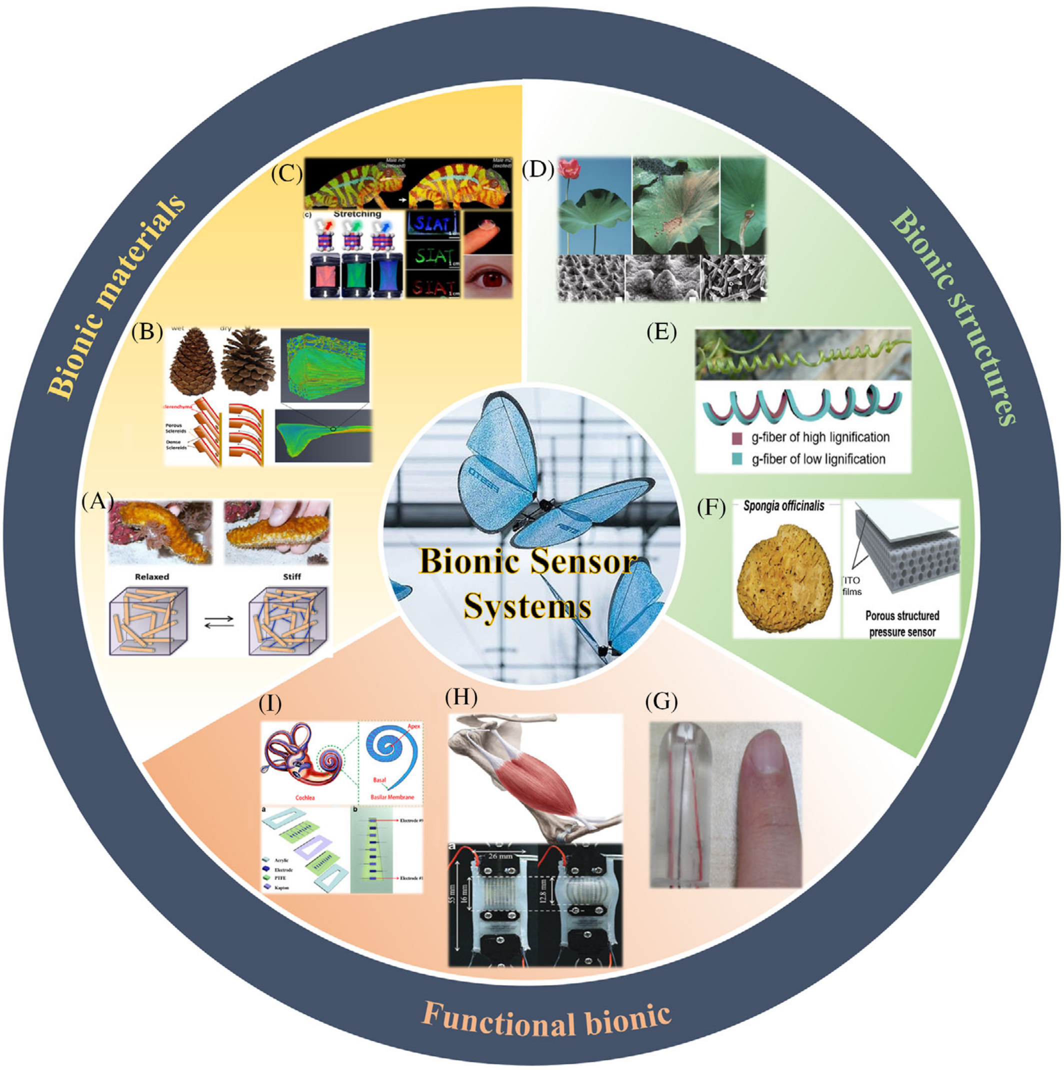

FIGURE 1 Bionic strategies of bioinspired sensor systems. (A) Stimuli-responsive polymer inspired by sea cucumber. Reproduced with permission.[21] Copyright 2008, AAAS. (B) Synthetic hygroscopic composites inspired by pinecone. Reproduced with permission.[22] Copyright 2021, Elsevier. (C) Mechanochromic photonic films inspired by chameleon. Reproduced with permission.[23] Copyright 2017, American Chemical Society. (D) Superhydrophobic material inspired by lotus leaves. Reproduced with permission.[24] Copyright 2017, Springer. (E) Adaptive tendril coiling structure inspired by climbing plants. Reproduced with permission.[4] Copyright 2017, American Chemical Society. (F) Porous structure inspired by spongia. Reproduced with permission.[25] Copyright 2016, WILEY-VCH. (G) Tactile sensor inspired by finger. Reproduced with permission.[26] Copyright 2017, Elsevier. (H) Microfluidic sensors for proprioceptive feedback. Reproduced with permission.[27] Copyright 2019, Mary Ann Liebert (I) Membrane acoustic sensor for frequency selectivity. Reproduced with permission.[28] Copyright 2018, Springer

materials, including metallic, ceramic, and polymeric materials, and so forth.[30] Among them, polymeric bionic materials have made outstanding contributions as sensing units or performance-enhancing materials in sensing systems. For example, different ferroelectric polymer materials can not only convert photoelectric signals like the retina,[31] but also sense temperature like the skin.[24] Hydrogel polymer materials have different functions through different manufacturing methods.[32] One option is to use a unique polymerization method to create synthetic polymer hydrogels, that can impart new properties to sensing systems. The other employs biotechnology to create biological macromolecule hydrogels that can respond to pH, temperature, ion concentration, and so forth.[33,34] Given the limitations of existing sensors, this kind of bionic strategy needs to fully understand the characteristics and underlying mechanisms of biological materials and manufacture bionic materials artificially to construct bioinspired sensors, so as to improve the properties of existing sensors,[35] such as stimulus responsiveness and unique mechanical properties. Understanding how molecules and materials respond to stimuli for natural sensing system function has become the goal of designing biomimetic sensing materials. The underlying mechanism's explanation is not only biologically significant, but it also paves the way for the development of materials that mimic natural functions or use comparable design approaches to impart these features to synthetic materials.[36,37]

Ingeniously designed by nature, some natural materials exhibit effective sensing and actuating functions. For example, sea cucumbers can quickly change the hardness of the dermis to defend against predators (Figure 1A),[21] pinecone scales are deformed by moisture absorption (Figure 1B),[22] chameleons can change skin color depending on the environment or mood (Figure 1C),[23,38] flytraps can close the clamp rapidly after perceiving the action of insects.[39] Stimuli-responsive polymers have great potential as sensing materials, which can change their molecular conformations upon specific external stimuli and subsequently alter their macroscopic properties by shrinking, wrinkling, bending, twisting, or volume change.[40–43] By adjusting the contact between collagen fibers, sea cucumbers can change the internal stiffness of their dermis. Inspired by this, to replicate the sea cucumber dermis, Weder et al.[21] created nanocomposites comprising cellulose nanofibers embedded in rubbery ethylene oxide-epichlorohydrin copolymers. The tensile modulus of the material decreases from 800 MPa to 20 MPa when it is placed in an aqueous medium, where water serves as a hydrogen bond breaker, and the material softens dramatically. Shape memory nanocomposites have also been created using switching principles found in the skin of the sea cucumber.[44,45] Based on the stimulus responsiveness of bionic materials, various types of bioinspired sensor systems have been developed to sense different environmental signals such as temperature, humidity, pH, light, and electromagnetic fields.[2,46–50]

The miniaturization and integration of the sensor system put higher demands on the mechanical properties of materials and structures. For example, strength and toughness are often mutually exclusive.[51] Natural materials show superior mechanical properties due to the optimal component ratio.[35,52–54] Many researchers have been devoted to develop lightweight, high-strength, and durable bionic materials inspired by biological materials such as cancellous bone, spider silk, seashell nacre,[52,55–58] which could endow the miniaturized, integrated bioinspired sensor system higher stability and reliability. To perform specific tasks, natural materials frequently include multiscale anisotropic structures. Bone, for example, is made up of cross-linked collagen fibers embedded in plate-like hydroxyapatite (HAp) nanocrystals in a highly organized staggered configuration. By implanting biocompatible hydrogels in delignified wood and in situ mineralization of HAp nanocrystals glue composite, Wang et al.[59] created hydrogels with excellent anisotropy, rigidity, and osteoconductivity, which provides more possibilities for the optimization of bionic sensor systems.

2.2 | Bionic structures

The strategy of bionic structures is to take inspiration from macroscopic or microscopic biological structures in nature to design the overall structure or primary functional parts of the devices to achieve desired capabilities. For example, eggshells, leaves, bamboo, spider webs, and other biological structures have advantages in structural weight, mechanical load capacity, and cost benefits.[60–62] The biological structures of animals and plants have offered a lot of inspiration for the design of bioinspired sensor systems. Bionic structures such as arches of foot,[63] fish scales,[64] plant surface,[65] and porous spongy[25] are frequently used in sensors, particularly pressure and strain sensors.

The construction of super-wetting bionic materials is the most common example of mimicking the surface microstructure of biomaterials. Super-wettable natural materials have long been recognized, but it wasn't until the last two decades that scientists began to study and imitate the microscopic structure of super-wettable surfaces found in nature.[66–72] By exploring microstructures of natural super-wettable materials such as super-hydrophobic lotus leaves (Figure 1D),[24,73–75] super-hydrophilic spider silk[76–79] and underwater super-oleophobic fish scales,[80] super-wetting materials are widely used in sensor systems. Bioinspired sensor systems made of super-hydrophilic materials may absorb body fluids more effectively than ordinary electrochemical sensors, which are useful for body fluid detection and analysis.[81,82] When employing a super-hydrophobic material, the sensor system possesses specific functions such as waterproof and self-cleaning.[83,84]

The tendrils of climbing plants (Figure 1E) are extremely sensitive to their surroundings. The unique structure allows them to grow on various supports depending on the circumstances.[85,86] Based on an ultra-stretchable bionic tendril structure, Cheng et al.[4] devised a novel device with adjustable conductivity and mechanical properties. The elastic buffer connection effect of this unique coiling structure makes conductive tendrils ultra-stretchable, increasing the stretchable range from 225% to 2000% and significantly improving conductive retention when compared to traditional conductive yarns: resistance increases from 24.6% to 9.2%. The bioinspired device incorporates the capacities of mobility, actuation, and sensing.

Many animals have sensitive sensory hairs, such as the antennae of insects[87,88] and whiskers of mammals.[89–91] The particular structure can sense tiny air currents in all directions, allowing them to navigate, control flight, and avoid danger, which is a novel concept for fluid motion sensors.[92–94] To detect low-speed fluid, Matthew R. et al.[95] proposed a hair-plug device. The response of the artificial hair sensor to steady boundary layer airflow was detected by a Blasius flat plate, and the boundary layer was characterized by a hotwire anemometer.

The most basic need of electronic skin is to achieve the requisite sensitivity to external stimulus.[96] Inspired by multilayered porous structures of spongia offilinalis, Kang et al.[25] created a pressure sensor with high sensitivity (0.63 kPa^{-1}) and extremely low-pressure detection of 2.42 Pa employing a bionic porous dielectric layer (Figure 1F). Based on the porous bionic sensor, a 15×15 array sensor system was fabricated for real-time tactile sensing in different modes.

2.3 | Functional bionic

The third strategy, functional bionic, aims to achieve similar functions to biological sensory systems through engineering technological approaches. This strategy needs a deeper understanding of biological sensing mechanisms rather than directly imitating natural biological materials and structures. Bionic materials and structures are frequently used to improve the performance of sensing systems or to give them new capabilities (self-healing, self-cleaning, etc.). Unlike bionic materials and structures, functional bionics is more focused on sensor-detecting functions, such as emulating natural species' five senses (visual, auditory, olfactory, gustatory, and tactile). After fully understanding the physiological processes of the organism, a variety of direct or indirect bionic techniques can be utilized to construct bioinspired sensor systems.

Inspired by the tactile perception function of the fingertips, Yi et al.[26] designed a bioinspired fingertip for surface roughness discrimination (Figure 1G). The device consists of two PDMS layers, a PMMA rod, and two perpendicular PVDF films. The PDMS layers of different stiffness can simulate the elastic properties of the dermis and epidermis of the skin. For prosthetic fingertips, the PVDF layer serves as Meissner's corpuscles, and the PMMA rod serves as the bone.

Artificial muscle is a popular technology in robots and prosthetics, usually requiring external driving devices and complicated position sensors, which are inconvenient in practical applications.[27] The Golgi tendon or[97] gan and the muscle spindle can offer real-time location and force feedback to the muscle.[98,99] Inspired by this, Wirekoh et al.[27] created a novel artificial muscle with an integrated bioinspired sensor that provided position and force information (Figure 1H) and verified its compatibility with wearable devices.

Cochlea is a structure that conducts and senses sound waves, which is an essential organ for creatures to sense sound. Traditional cochlear implants need external energy input, which complicates patient treatment and rehabilitation. After understanding the mechanism of the frequency selective function of the cochlea, Liu et al.[28] demonstrated a bionic device that can achieve the functionalities of frequency selection and self-powered at the same time by utilizing a membrane sensor based on triboelectric technique (Figure 1I).

3 | BIOINSPIRED SENSORS WITH DIFFERENT WORKING MECHANISMS

According to the working mechanism, bioinspired sensors can be mainly classified into four categories: piezoresistive, capacitive, triboelectric, and piezoelectric (Figure 2).[100–103] Each type of bioinspired sensor has its unique sensing properties and applications. Piezoresistive sensors are made from piezoresistive materials, which can change the resistivity when mechanical strain occurs. As one of the earliest commonly used sensors, piezoresistive sensors are used to measure pressure, tension and other physical quantities related to force.[104] Mostly, piezoresistive sensors are simple in structure, low in cost, and durable. Capacitive sensors use various types of capacitors as sensing components to transform measured physical quantity into capacitance changes, which can

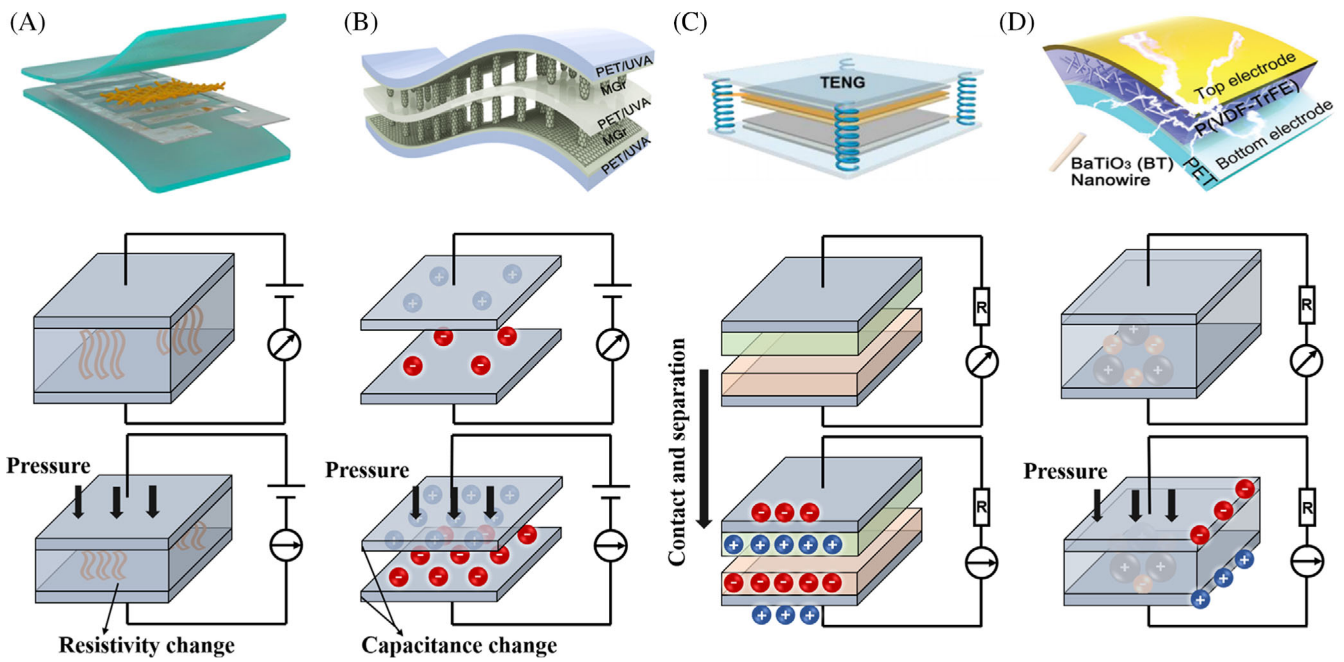

FIGURE 2 Different working principles of bioinspired sensors. (A) Piezoresistive sensor. Reproduced with permission.[100] Copyright 2019 American Chemical Society. (B) Capacitive sensor. Reproduced with permission.[101] Copyright 2019 American Chemical Society. (C) Triboelectric sensor. Reproduced with permission.[102] Copyright 2020 American Chemical Society. (D) Piezoelectric sensor. Reproduced with permission.[103] Copyright 2018 WILEY-VCH

work over a large temperature range compared to other types of sensors. Triboelectric and piezoelectric type sensors can directly convert mechanical energy into electrical signals without the need for external power sources, making them especially suitable for mobile and distributed sensing applications. Triboelectric type sensors are based on the triboelectric effect and electrostatic induction, with wide ranges of material selection and working frequency.[105] Piezoelectric type sensors are based on the piezoelectric effect with an output proportional to the applied force, which has a high resolution for varied frequencies and strains.[106]

Table 1 summarizes the four basic types of bioinspired sensors from bionic strategies, bionic sources, performance indicators (sensitivity, response time, measuring range, durability) and sensing functions. It can be seen from the table that piezoresistive and capacitive bioinspired sensors mainly adopt the strategies of bionic materials and bionic structures, which are widely used for pressure and tactile sensing. These two types of bioinspired sensors mainly focus on improving sensing performance, surface of plant surfaces,[107,108] natural hierarchical[3,121] and interlocking structures of human skin[109,111,122] are common bionic sources. As can be seen from the table, the sensitivity of piezoresistive sensors is mostly 10–1000 kPa^{-1}, while the sensitivity of capacitive sensors is 0–1 kPa^{-1}. The measurement range of capacitive sensors is generally larger than that of piezoresistive sensors. For triboelectric and piezoelectric bioinspired sensors, functional bionic strategies are adopted except for bionic materials and bionic structures. Some specific sensing functions can be realized by mimicking the functions of natural sensory systems, such as gas sensing by imitating the olfactory system[114] and sound recognition by imitating hearing hair cells.[119] Furthermore, these two types of bioinspired sensors are self-powered, allowing for active sensing without a power supply.

3.1 | Piezoresistive bioinspired sensors

The working mechanism of piezoresistive sensors is the piezoresistive effect produced by piezoresistive materials when they are elastically deformed.[104,123,124] When mechanical strain is applied, the piezoresistive effect causes a change in the resistivity of a semiconductor or metal (Figure 2A).[100,125,126] As one of the first products of MEMS technology, piezoresistive sensors have made great progress with the development of microelectronics.[127] Piezoresistive sensors are widely used in automotive industry, biomedical applications and household appliances because of their tiny size, low weight, high-pressure resolution, and excellent frequency response.[127–131] Recent research has shown that piezoresistive sensors are increasingly being used in the biomedical field. The applications in electronic skin, exoskeletons, and prostheses place higher demands on the stability, biocompatibility, and sensitivity of piezoresistive

TABLE 1 The summarization of bioinspired sensors

	Bioinspired sensors			
Types features	**Piezoresistive**	**Capacitive**	**Triboelectric**	**Piezoelectric**
Bionic strategy	Bionic materials[107–109] Bionic structures[94,110]	Bionic materials[111–113] Bionic structures[25,93]	Functional bionic[114–116] Bionic materials[117] Bionic structures [118]	Functional bionic[26,119,120] Bionic structures[92]
Bionic source	Plant surface[107,108] Human skin[109] Stereocilia[94,110]	Human skin[111] Komochi Konbu[113] Spongia[25] Plant surface[112] Microhair[93]	Plant surface[117] Ion channels[118] Eardrum[116] Auditory system[115] Olfactory epithelium[114]	Human skin[120] Hair[92] Fingertip[26] Corti cells[119]
Sensitivity	120 kPa^{-1}[108] ~10^3 kPa^{-1}[111] 83.9 kPa^{-1}[109] 1.5 Ω μm^{-1}[130] 30 mV (m s^{-1})$^{-1}$[92]	0.293 kPa^{-1}[112] 0.171 kPa^{-1}[160] 0.63 kPa^{-1}[62] 0.815 kPa^{-1}[158] 0.56 kPa^{-1}[91]	127.22 mV kPa^{-1}[168] 51 mV Pa^{-1}[220] 110 mV dB^{-1}[167]	2.21×10^{-3} V Pa^{-1}[90]
Response time	< 16.7 ms[121] 30 ms[107]	162 ms[113] 38 ms[112]	< 6 ms[116]	
Measuring range	0.88 Pa-32 kPa[107] 0.02–30 kPa[109]	0–250 kPa[113] 0–90 kPa[25] 0–50 N[112]	0.1–3.2 kHz[116] 100–5000 Hz[115]	1–500 Hz[92] 100–1600 Hz[119]
Durability	> 1000 cycles[107] > 28 000 cycles[108]	> 1000 cycles[111] > 10 000 cycles[113] > 10 000 cycles[25] > 3000 cycles[93]	> 1000 cycles[114] > 5000 cycles[117] > 50 000 cycles[118] > 40 000 cycles[116]	
Functions	Flow sensing[94,110] Tactile sensing[94,110] Pressure sensing[3,107–109,121]	Tactile sensing[25,111,112] Pressure sensing[93,113]	Tactile sensing[117] Acoustic sensing[115] Pressure sensing[116] Gas sensing[114]	Pressure sensing[120] Temperature sensing[120] Acoustic sensing[92,119] Flow sensing[92] Tactile sensing[26]

sensors. Structural design of the piezoresistive materials is one of the most effective ways to tackle this problem, and the use of bionic strategies allows piezoresistive sensors to be further optimized.[110,132–136]

The leaves of plants have distinctive microstructures and the ability to perceive and respond to the surrounding environment. Wang et al.[137] presented a sandwich-structured flexible electronic sensor with a micro-patterned lotus leaf-like substrate layer (Figure 3A). Compared with monotonous microstructure, the hierarchical structure has a large contact area, leading to high sensitivity when applying pressure. The sensitivity of the device can reach about 0.58 kPa^{-1} in the range of 300–400 Pa, which could be used to detect respiration, acoustic vibration, and so forth. Nie et al.[138] formed a hierarchical structure by mimicking the structure of the surface of a lotus leaf and creating micro-cracks in the layer under pressure. A PDMS substrate with an ordered mountain pattern with micron-level secondary and tertiary ridges was produced by recreating the layered microstructure of the banana leaf surface (Figure 3B). When the pressure is less than 400 Pa, the sensitivity of this E-skin device with the novel structure can approach 10 kPa^{-1}, and the stability is excellent (> 10 000 cycles). It has excellent performance in voice recognition and pulse monitoring.

Human skin is a sensory system with a natural hierarchical structure that can respond to changes in the external environment rapidly.[142–145] Mxenes have good metal conductivity and surface hydrophilicity, which are considered the excellent active layers of piezoresistive sensors.[146] Based on the skin's unique structure and taking Mxenes as the active layer, Wang et al.[139] constructed a pressure sensor with a sensitivity of 24.63 kPa^{-1} and a response time of 14 ms based on interlocked structures and Ti3C2/natural microcapsule film (Figure 3C). Cheng et al.[140] created a sensitive (151.4 kPa^{-1}) and stable (over 10 000 cycles) Ti3C2Tx-based device with random bionic micro spinous structures (Figure 3D). The two bionic Mxenes based sensors showed good performance in detecting and recognizing physiological signals like finger movements and human pulses.

In addition to the hierarchical structure, the micro-crack structure seen in arthropods is also utilized for enhancing piezoresistive sensor sensitivity.[141,147–151] Small variations in mechanical stress are detected by spiders through crack-like fissure organs near the leg joints.[147] Inspired by the micro-crack structure of the spider, Kang et al.[141] demonstrated an ultrahigh sensitivity device (Figure 3E), and the gauge factor exceeded 2000 in the range of 0%–2% strain. Liu et al.[84] create a novel piezoresistive sensor with a superhydrophobic surface and micro-crack structures inspired by the lotus leaves and scorpion's vibration-sensing organ, respectively. The paper-based bionic piezoresistive sensors with waterproofness, high sensitivity (gauge factor of 263.34) and fast responsiveness (78 ms) demonstrated potential in detecting human physiologic signals as well as monitoring subtle underwater vibrations.

3.2 | Capacitive bioinspired sensors

A standard capacitive sensor is composed of upper and lower electrodes, dielectric, and substrate. The capacitance of the parallel plate capacitor can be calculated by the formula $C = \varepsilon A/d$, where ε refers to electric constant of dielectric, A and d are the overlap area and distance between the two plates. Therefore, capacitive sensors can be divided into three types: variable distance type, variable area type, and variable medium type.[152–155] Many types of sensors use capacitive sensing, including sensors to measure pressure, displacement, acceleration and humidity.[152] The capacitive sensor performs well in industry, military and medicine because of its high sensitivity, quick reaction, and low-power consumption.[111,156–158] The ordinary capacitive sensor is limited by its size, because when the capacitive sensor's volume

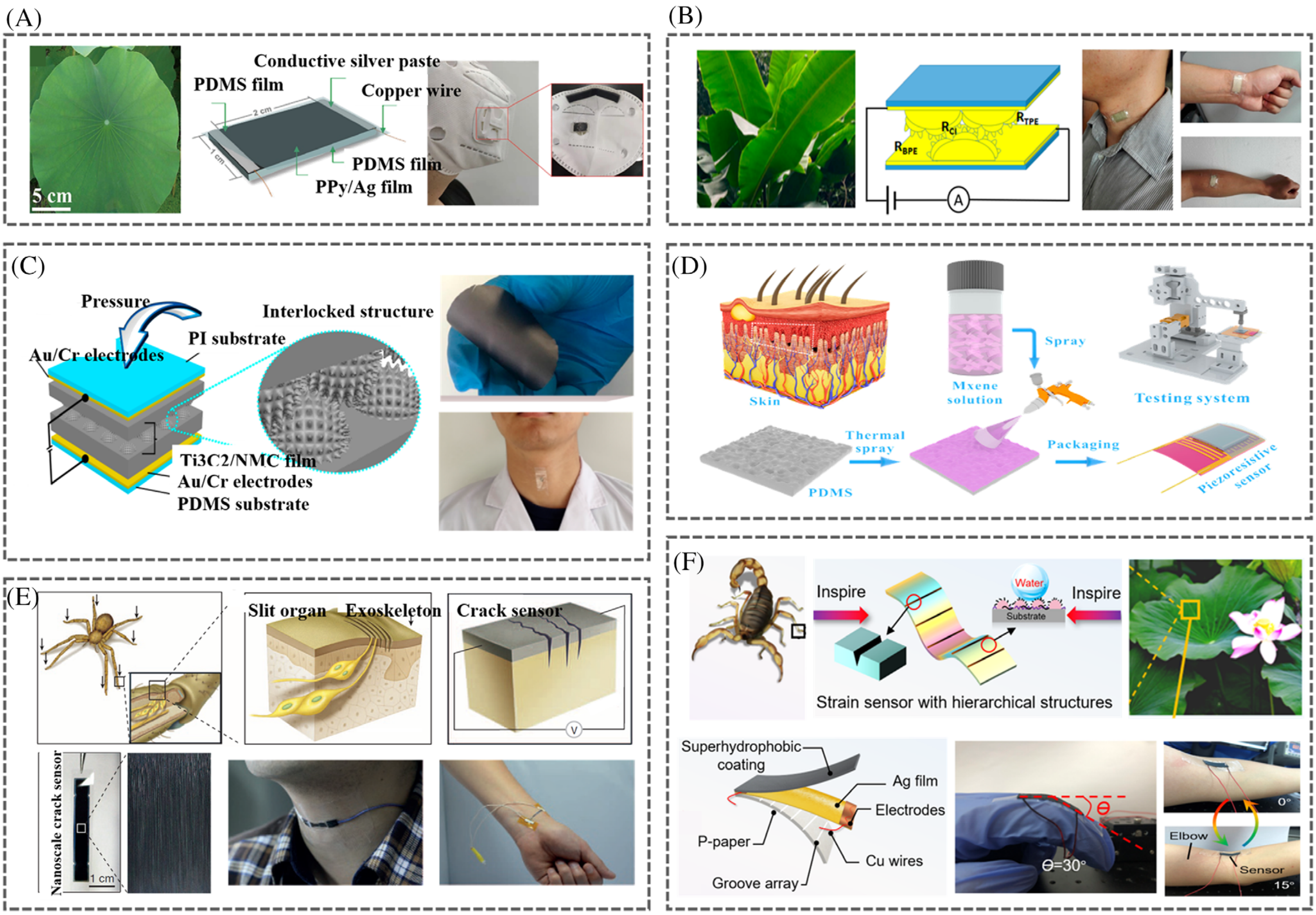

FIGURE 3 Piezoresistive bioinspired sensors. (A) Physiological signals monitoring inspired by lotus leaf. Reproduced with permission.[137] Copyright 2021, Elsevier. (B) Piezoresistive electronic skin inspired by banana leaf. Reproduced with permission.[138] Copyright 2017, American Chemical Society. (C), (D) MXene based flexible pressure sensors inspired by human skin. Reproduced with permission.[139,140] Copyright 2019, American Chemical Society. Copyright 2020, American Chemical Society. (E) Ultrasensitive mechanical crack-based sensor inspired by the spider sensory system. Reproduced with permission.[141] Copyright 2014, Macmillan Publishers Limited. (F) Superhydrophobic, and paper-based strain sensor inspired by lotus leaf and scorpion. Reproduced with permission.[84] Copyright 2021, American Chemical Society

is tiny, the fringe effect becomes highly noticeable. The fringe effect and parasitic capacitance have an impact on the sensor, resulting in a reduction in sensitivity and measurement accuracy.[159] The employment of bionic strategies to enhance capacitive sensors is becoming increasingly popular in research.[152] The sensitivity and measurement accuracy of capacitive sensors are increased by using bionic techniques to modify the materials and structures of the two capacitive plates and dielectric, which makes it possible to break through the fringe effect limitation in device miniaturization.

Above mentioned, according to the working mechanism of the capacitive sensor, the performance of the sensor can be enhanced by optimizing the materials and structures of the electrode plate and dielectric adopting bionic strategies.[160] Tactile capacitive sensors' performance can be improved by optimizing the microstructure of electrodes.[65,161–163] Boutry et al.[164] reported a bionic soft E-skin based on an array of capacitors (Figure 4A). The e-skin with an electrode plate adopting the interlocking structure of human skin can record normal and tangential force simultaneously. The design inspired by the sunflower space pyramid structure improves the sensitivity and cyclic stability of the device. In a low-pressure range, the sensitivity of the sensor to normal force and tangential force can reach $0.19 \pm 0.07\ kPa^{-1}$ and $3.0 \pm 0.5\ Pa^{-1}$, respectively, and the response time is under milliseconds. Li et al.[112] presented a bionic capacitive sensor, which is constructed by two flexible micropatterned electrodes duplicated from lotus leaves and polystyrene microspheres as the dielectric (Figure 4B). In the case of optimal size, the sensitivity of the sensor can reach $0.815\ kPa^{-1}$, the minimum detection pressure is 17.5 Pa, and the response time is 38 ms.

The sensitivity of the capacitive sensor is also affected by the structure of dielectric materials. Inspired by human hair skin, Zhou et al.[165] introduced a flexible micro cilia array as a dielectric layer between the electrode plates. The shape of the microciliary array can be controlled by the magnetic field and composite material mass ratio (Figure 4C). The capacitive pressure sensor showed a wide detection range (2- 200 kPa) and a high sensitivity ($0.28\ kPa^{-1}$ in the range of 0–10 kPa). Employing a bionic komochi konbu structure in the dielectric layer, Wang et al.[113] presented a capacitive sensor that can detect pressure in a wide range (0–250 kPa) with a sensitivity of $0.171\ kPa^{-1}$, while the common flat sensor has a sensitivity of $0.00835\ kPa^{-1}$ in the range of 0–5 kPa. The existence of the microstructure gives a greater basic capacitance of the device and makes it easier to detect changes in capacitance (Figure 4D).

3.3 | Triboelectric bioinspired sensors

Triboelectric nanogenerators (TENGs) can convert mechanical energy into electrical energy based on the triboelectric effect and electrostatic induction.[136,166–168] TENG-based sensors provide a number of benefits,

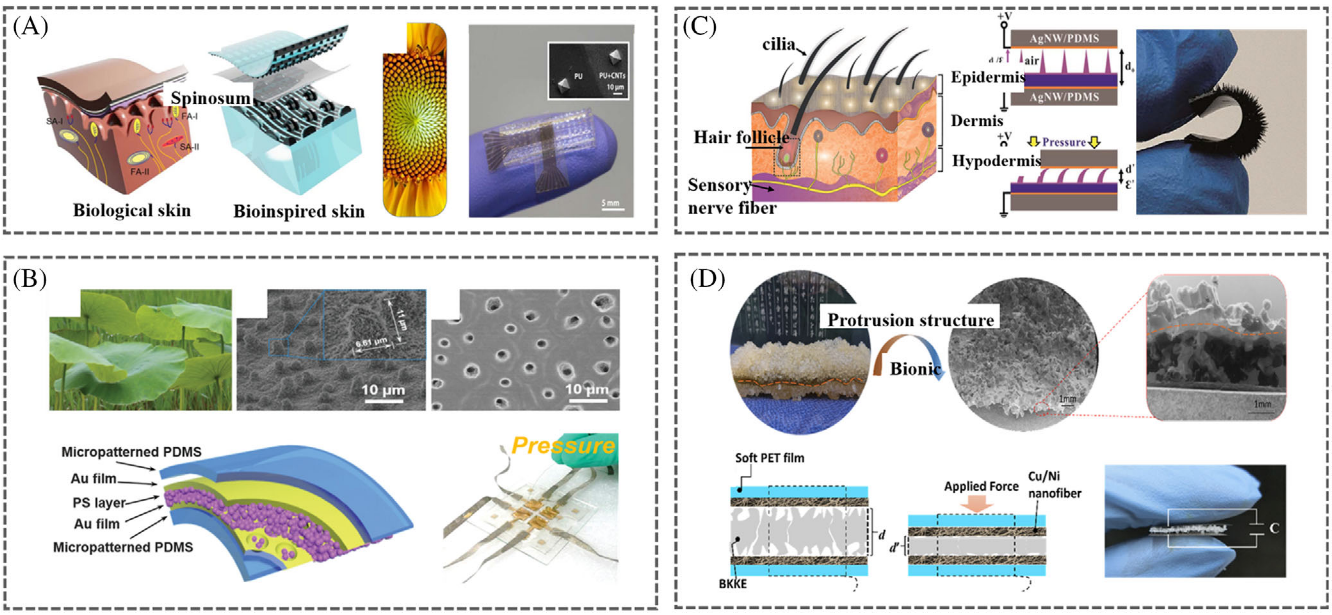

FIGURE 4 Capacitive bioinspired sensors. (A) Hierarchically patterned e-skin inspired by human skin and sunflower. Reproduced with permission.[164] Copyright 2018, AAAS. (B) Tactile sensor based on micropatterned dielectric layer inspired by lotus leaf. Reproduced with permission.[112] Copyright 2016, Wiley-VCH. (C) Flexible capacitive pressure sensor with a hair-like micro cilia array. Reproduced with permission.[165] Copyright 2019, The Royal Society of Chemistry. (D) Wide-range, bendable, and high sensitivity capacitive pressure sensor inspired by Komochi Konbu. Reproduced with permission.[113] Copyright 2019, American Chemical Society

including active sensing properties, high-voltage output, low-frequency applicability, ease of manufacture, low cost, diverse structure, and wide choice of materials.[169–171] The structure of the substrate layer, the electron affinity of the friction layer materials, are critical factors impacting the mechanical and electrical properties of triboelectric sensors. The coupling of bionic strategies with TENG technology gives a wealth of ideas for improving the performance and expanding the new functions of triboelectric type sensors.

Guo et al.[115] developed a novel bioinspired auditory system based on TENG with an ultra-high sensitivity (110 $mV\cdot dB^{-1}$) and a broad response range (100–5000 Hz), thanks to the system optimization design for sectorial inner boundary architecture (Figure 5A). The fabrication of TAS (triboelectric auditory sensor) can be divided into preparation of the electrodes, and assembly of the device. The FEP film with nanostructure was adhered to the Au layer by vacuum magnetron sputtering which is the upper electrode, the Kapton film covered with Au layer was chosen as bottom electrode. At last, the two parts were assembled using the A4 paper as the spacer to get tunable gaps. The surface morphology of the nanostructure in FEP film was characterized by field-emission scanning electron microscopy. The TAS was integrated with an intelligent robot to realize human-machine interaction functions like music control and speech recognition.

Yao et al.[117] took the microstructures of the Calathea zebrine leaf as a plate to construct friction layers with interlocking structures (Figure 5B). It is found that the sensitivity (127.22 $mV\cdot kPa^{-1}$) of the e-skin sensor with the bionic interlocking structures and the micro-surface burr is increased by 14 times compared to that of the sensor with flat tribo-layers. The tactile sensing ability of the bioinspired sensor is reflected in human-machine interaction, such as the degree of bending and pressure of each finger when the artificial hand with the e-skin shakes the human hand.

Wang et al.[172] fabricated a bionic-designed multi-functional TENG-based sensor for tactile sensing (Figure 5C). The graphene/PDMS layer was built and composited with the hydrophobic PTFE, which was inspired by the sponge structure. This self-powered sensor has a temperature resolution of 1 K and a high-pressure sensitivity of 15.22 kPa^{-1}. Inspired by biological cells, Wang et al.[173] constructed a stretchable TENG-based skin utilizing a patterned interconnected cellular structure with an open-circuit voltage of 57 V (Figure 5D). The TENG-based skin used saline as an electrode and a rubber layer as a friction layer, which can handle a wide range of strains (up to 600%).

Flexible wearable sensors that can work long-term underwater are of great significance for underwater practitioners, but some challenges must be overcome, such as continuous power supply. Inspired by the structure of ion channels in electric eel, Zou et al.[118] designed a self-powered stretchable underwater sensor based on a bionic mechanosensitive channel and triboelectrification effect (Figure 5E). The bionic underwater sensor can produce an open-circuit voltage exceeding 10 V by converting mechanical energy from underwater motions into electricity, allowing for the active monitoring of the underwater movements of the human body.

Due to the specific structure of their mouths, male frogs can convert a small contraction of the mouth muscles into a considerable distortion of the outer vocal cord capsule when vocalizing. Inspired by the structure of the frog's mouth, Zhou et al.[174] presented a bioinspired TENG-based sensor to monitor the micro-vibration of the masseter muscle in real-time (Figure 5F). The TENG-based BTUSE sensor was composed of sensing film with PDMS support components, AgNWs bottom electrode, AgNWs/BaTiO3 NPs/PDMS friction layer and carbon-based top electrode. The morphology and structure of the materials were characterized by using a field emission scanning electron microscopy. The crystalline phases of BaTiO3 NPs and AgNWs were measured by an X-ray diffractometer. The bionic sensor has a sensitivity of 54.6 $mV\cdot mm^{-1}$ and a detecting range of 0–5 mm for micro-vibration monitoring. Combining the bioinspired electromechanical sensor and machine learning can convert the masseter muscle's micro-vibration of the human body into the control command of the human-machine interface to realize the muscle-triggered communication function.

3.4 | Piezoelectric bioinspired sensors

Piezoelectric sensor, which can also spontaneously convert mechanical energy into electrical signals. When the asymmetric crystal is subjected to an external force in one direction, electric polarization occurs inside, and charges of different polarities are generated on two surfaces perpendicular to the polarization direction. Once the external force is removed, the crystal returns to an uncharged state. When the direction of the external force changes, the polarity of the charge also changes. The amount of charge generated by the crystal is proportional to the magnitude of the external force.[106,175–177] With the benefits of high repeatability, wide operating frequency range, simple structure, and high signal-to-noise ratio, piezoelectric sensors are usually used for the measurement of pressure, strain, and acceleration.

Piezoelectric sensors can work over a wide frequency range, and their output is highly related to frequency, which makes them suitable for frequency identification.

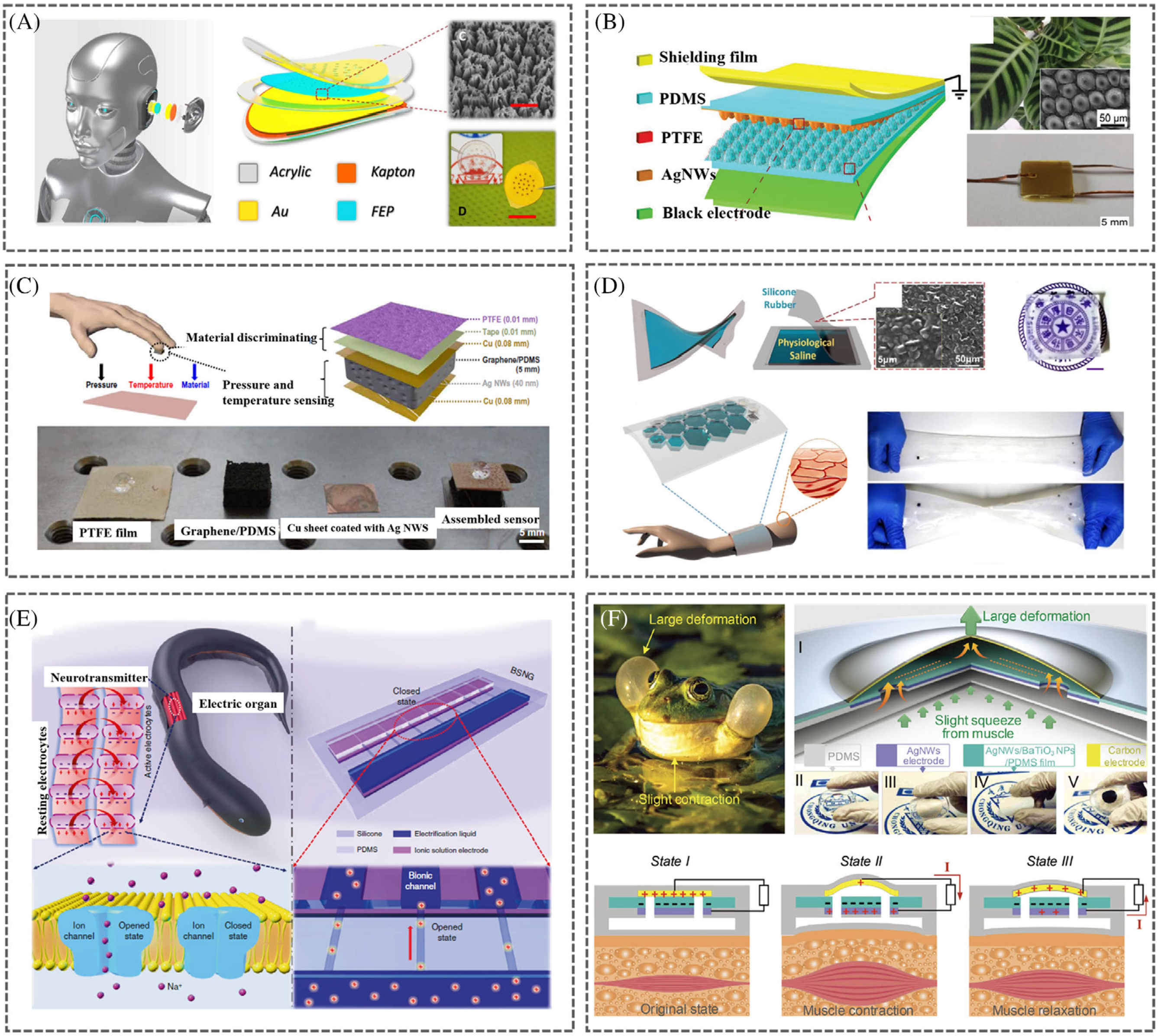

FIGURE 5 Triboelectric bioinspired sensors. (A) Self-powered triboelectric auditory sensor. Reproduced with permission.[115] Copyright 2018, AAAS. (B) Self-powered electronic skin for robotic tactile sensing inspired by Calathea zebrine leaf. Reproduced with permission.[117] Copyright 2019, Wiley-VCH. (C) Hierarchically patterned tactile sensor inspired by sponge structure.[172] Reproduced with permission. Copyright 2020, AAAS. (D) Energy-harvesting skin with patterned interconnected cellular structures. Reproduced with permission.[173] Copyright 2017, Elsevier. (E) Self-powered multi-position motion sensor for underwater monitoring. Reproduced with permission.[118] Copyright 2019, Springer Nature. (F) Self-powered muscle-triggered sensor inspired by frogs' croaking behavior. Reproduced with permission.[174] Copyright 2021, Wiley-VCH

Studies show that when the hair cells of the Corti organ in the cochlea are damaged, frequency discrimination is impaired, and sensorineural hearing loss occurs.[178,179] Lee et al.[119] were inspired by the working mechanism of hair cells and reported a flexible inorganic piezoelectric acoustic nanosensor (Figure 6A). The device separates the audible frequencies of the incoming sound through a trapezoidal silicone-based membrane to imitate human hair cells and realize their functions. Different vibrations can be generated at different positions of the device after receiving sounds of different frequencies within the audible range, and the corresponding electrical signals are generated under the piezoelectric effect. The device is very sensitive and can convert tiny vibrations of 15 nm into an electrical output of 55 μV.

Polyvinylidene fluoride (PVDF) has both a piezoelectric effect and a pyroelectric effect. Sensors based on PVDF can track dynamic signals such as the changes in

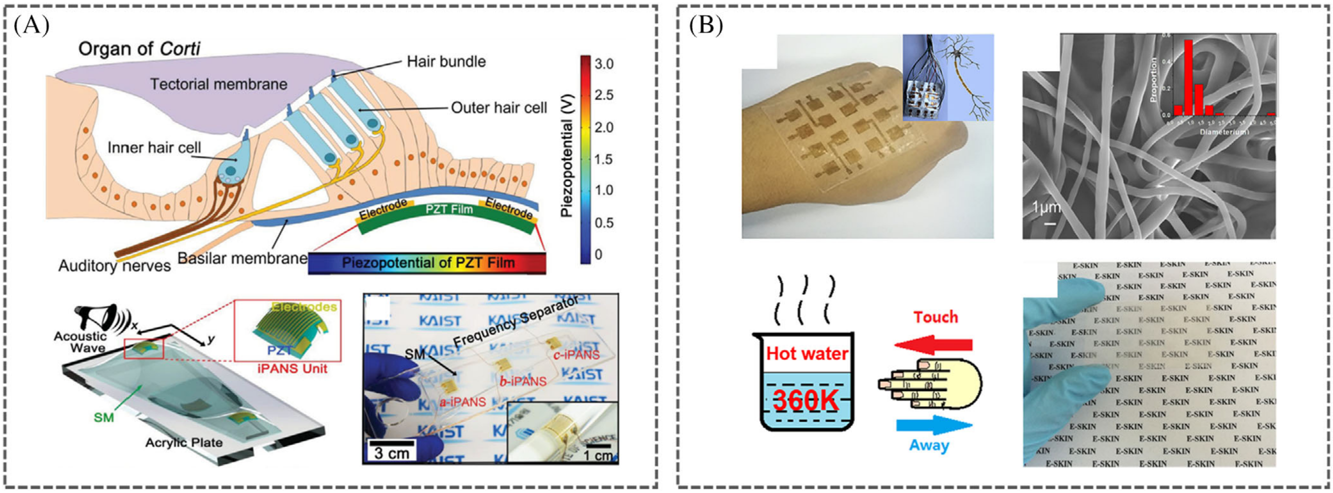

FIGURE 6 Piezoelectric bioinspired sensors. (A) Inorganic piezoelectric acoustic nanosensors inspired by hair cells. Reproduced with permission.[119] Copyright 2014, WILEY-VCH. (B) Single-electrode e-skin based on piezoelectric sensor. Reproduced with permission.[120] Copyright 2018, American Chemical Society

pressure, acceleration, and temperature. The single-electrode transmission of human nervous system signals is highly efficient and stable. Inspired by this, Wang et al.[120] fabricated a novel single-electrode piezoelectric nanogenerator e-skin based on PVDF nanofibers (Figure 6B). The device integrated steady-state strain sensing and pulsed pyroelectric signal sensing into a unit. The two kinds of signals can be collected at the same time are represented as square wave signals and pulse wave signals, respectively. In contrast to the triboelectric single electrode sensor, the sensor uses a capacitor as the potential reference rather than the ground wire. The single-electrode e-skin has good ductility. Besides, transparency can also be achieved when ITO is used as a bottom electrode.

3.5 | Other types of bioinspired sensors

The four types of bioinspired sensors mentioned above are mainly used to detect ordinary physical signals. Besides that, there are also electrochemical bioinspired sensors, biochemical bioinspired sensors, and other principles of bioinspired sensors. These bioinspired sensors are employed in various situations to detect chemical signals, biological signals or complex physical signals.

The electrochemical sensor is a kind of chemical sensor with the electrodes as sensing element.[180] When the target analyte is coupled with functionalized nanomaterials to accept or donate electrons on the electrode, the sensor performs electroanalytical detection.[181] Electrochemical sensors can be methodologically classified into four categories: potentiometry, amperometry, conductometry, and voltammetry.[182] Where potentiometry is the measurement of the potential between electrodes at a constant current. Amperometry is the measurement of the current between electrodes at a constant potential. Conductometry is the measurement of the conductivity of the specimen at a constant current, and voltammetry is the measurement of the electrode's load charge capacity as well as the current flow at different voltages.[181] The electrochemical sensor has the advantages of low cost and fast response time in the detection of body fluid biomarkers. The combination of electrochemical sensors with flexible devices and the employment of bionic strategies to realize noninvasive real-time body fluid monitoring is of great significance for healthcare.[183]

Since the biostability of the enzyme-catalyzed glucose electrochemical sensor is poor, it is necessary to develop a high-performance enzyme-free glucose electrochemical sensor, which depends on the design of new electrodes for enzyme-like activity. Gao et al.[184] fabricated an electrochemical Mn-NiO-based sensor with a bionic tremella-like structure to detect glucose in human serum (Figure 7A). The application of the biomimetic tremella structure increases the electrochemical surface-active area, thereby improving the detection sensitivity ($3212.52\ \mu A \cdot mM^{-1} \cdot cm^{-2}$) and efficiency.

The rhino nose of marine mollusks is a kind of biochemical sensor with telescopic characteristics, so it can show adjustable chemical sensing ability according to the position of the signal source.[189–191] Based on this inspiration, Wang et al.[185] introduced a stretchable and programmable electrochemical sensor (Figure 7B). The biomimetic stretch structure can be programmed to control the electrochemical surface-active area to change the sensitivity to glucose. The sensor realized a change of sensitivity from $195.4\ \mu A \cdot mM^{-1}$ to $14.2\ \mu A \cdot mM^{-1}$ under different percentages of strains and different glucose concentrations.

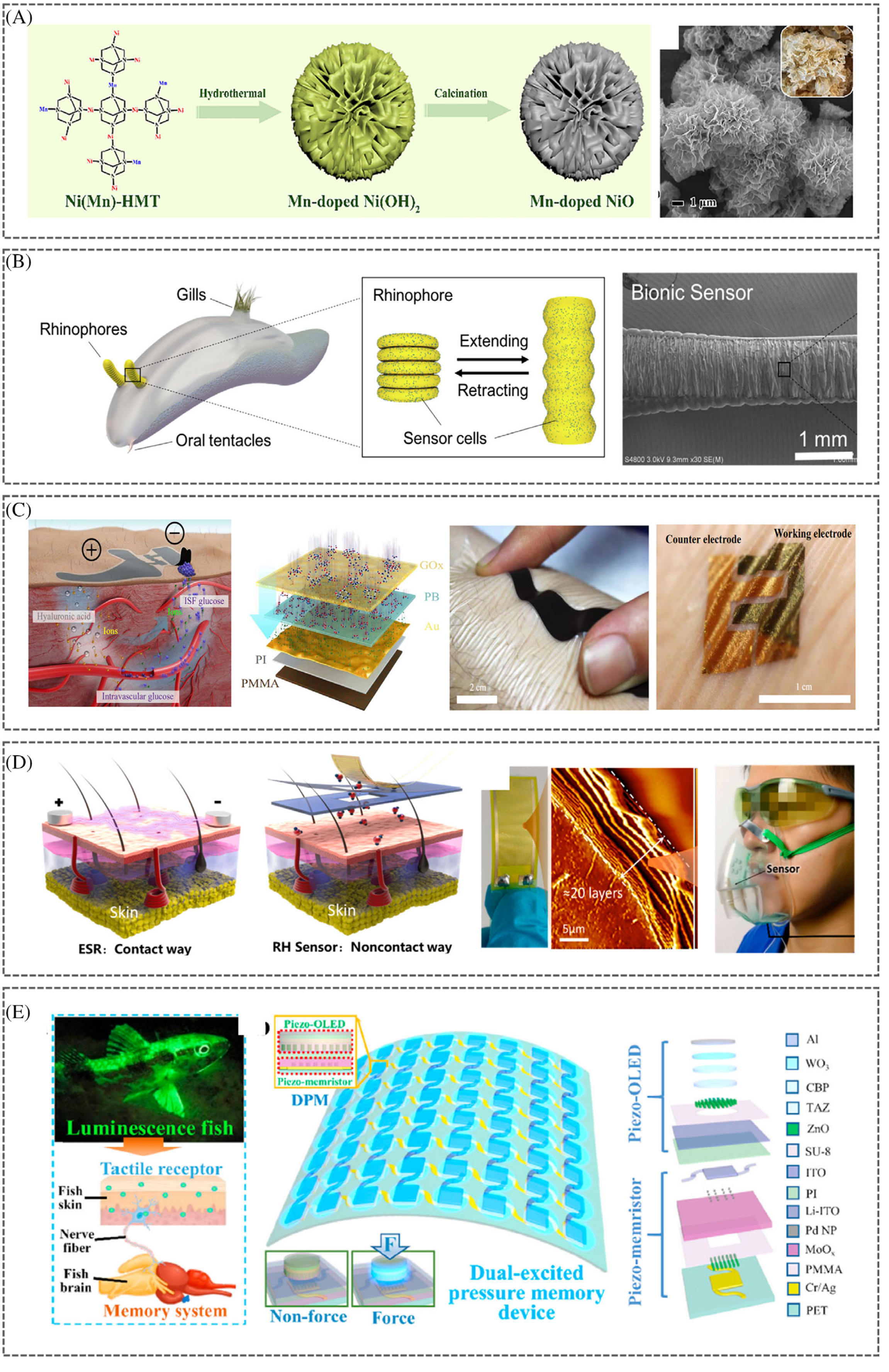

FIGURE 7 Legend on next page.

The glucose content of bodily fluids is just 1%–10% of blood glucose, hence it cannot accurately reflect blood glucose levels. Measuring glucose in the interstitial fluid (ISF) appears to be more promising compared with it.[186] Chen et al.[186] presented a skin-like fully noninvasive sensor for ISF blood glucose monitoring (Figure 7C). The electrochemical sensors are arranged in multilayered dune-like nanostructures for higher sensitivity and better electrochemical properties. The device consists of ultra-thin skin-like sensors and paper batteries that stick to the skin. Paper batteries can generate electrochemical dual channels under the skin to drive blood glucose from blood vessels to the skin surface. The ultra-thin (3 μm), skin-like sensor has high sensitivity (130.4 $\mu A \cdot mM^{-1}$), and noninvasive test data correlates 90% with real clinical blood glucose levels.

In organisms, the weak noncovalent molecular interactions between proteins and other proteins provide the basis for cell recognition and response to signals.[192] Biological enzymes can act efficiently based on hydrogen bonds, even reaching 106 times per second. This is because the strength of hydrogen bonds is not high and can be broken and formed continuously at room temperature.[193–197] Inspired by this, He et al.[187] reported a flexible humidity fluctuation sensor with high performance humidity sensing materials that can react differently to different relative humidity levels(Figure 7D). It has a wide humidity response range (0%–97%) and an extremely short response time (20 ms), which shows great potential in wearable psychological monitoring equipment.

Ordinary pressure sensors have no memory features and are solely used for real-time force measurement, making them unable to analyze the data further.[121,198] Luminous fish can perceive external stimuli, build tactile memory, and give feedback on them. Jiang et al.[188] presented a bionic e-skin that integrated piezo-OLEDs and piezo-memristor to imitate neuromorphic tactile system of the luminous fish (Figure 7E). This device shows the ability of memorizing output data, as well as the function of tactile sensing.

4 | APPLICATIONS OF BIOINSPIRED SENSOR SYSTEM

Due to their excellent sensing performance, such as high sensitivity, quick response, and strong stability, various bioinspired sensor systems have been successfully applied in many fields, including biomedicine, environmental monitoring, food inspection, intelligent robots, and human-machine interaction. With the help of bioinspired sensor systems, both humans and machines can gain better recognition of their own states and the surroundings. Human perception can be quantified, and machines can be endowed with specific perception. Here we mainly summarize the applications of bioinspired sensor system in health monitoring and human-machine interaction, as shown in Figure 8. For health monitoring applications, sensor system design is more concerned with its own sensing accuracy, comfort, biocompatibility, feedback signal visualization and so on, whereas human-machine interaction sensor system design focuses on stability and adaptability, durability, integration, and rapid response.

4.1 | Health care

Health issues have become a focus of attention in recent years with the advancement of society and medical technology. Flexible wearable technologies have given rise to new possibilities for personalized diagnosis and treatment.[200,202–204] Skin is one of the most important sensory organs of human beings and is the interface for information exchange between the inside and outside of the human body. Skin can also serve as an essential medical diagnostic interface for the human body. Real-time, long-term monitoring of the physiological state of the human body is one of the most effective ways to prevent disease. As a result, skin-like diagnosis systems have attracted a lot of interest.[205–207] Electronic skin is a sensor-based skin system that could be utilized for real-time monitoring of physiological signals in the human body.[139,201] The functions and performance of electronic skin are determined by sensor technology. The sensor technology based on bionic strategies offers a wealth of approaches for optimizing E-skin.

The micro-ridge interlocking structure between the epidermis and the dermis in the human fingertips amplifies various static and dynamic tactile signals and transmits them to the receiver. Inspired by the structure and function of fingertips, Park et al.[142] constructed a ferroelectric skin with high sensitivity to static and dynamic

FIGURE 7 Other types bioinspired sensors. (A) Sensitive glucose sensor with a tremella-like nanostructure. Reproduced with permission.[184] Copyright 2020, Elsevier. (B) Stretchable and programmable electrochemical sensor inspired by rhinophore. Reproduced with permission.[185] Copyright 2019, Elsevier. (C) Skin-like blood glucose sensor.[186] Copyright 2017, AAAS. (D) A bionic flexible humidity fluctuation sensor. Reproduced with permission.[187] Copyright 2018, American Chemical Society. (E) Pressure memory device based on piezo-OLED and piezo-memristor inspired by luminescence-fish. Reproduced with permission.[188] Copyright 2020, Elsevier

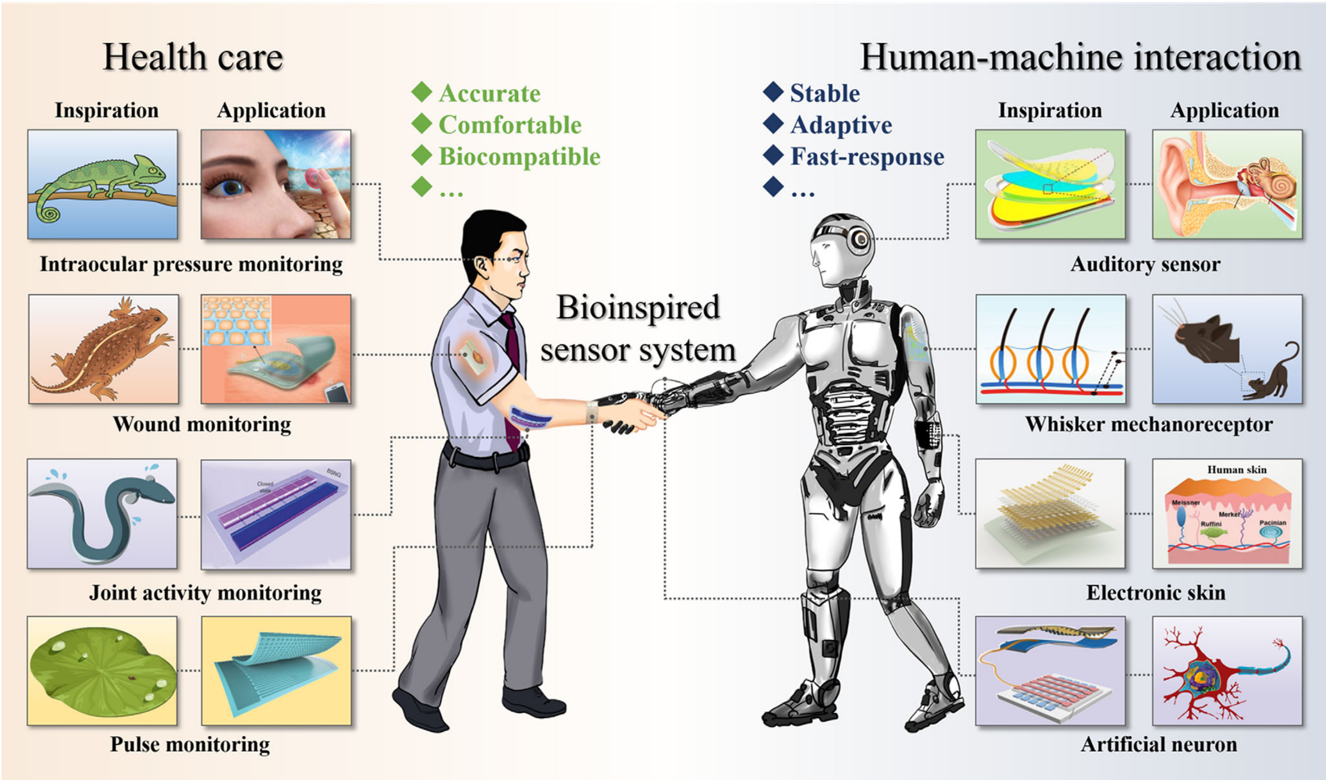

FIGURE 8 Applications of bioinspired sensor systems. Reproduced with permission.[199] Copyright 2020, The Royal Society of Chemistry. Reproduced with permission.[200] Copyright 2021, AAAS. Reproduced with permission.[118] Copyright 2019, Springer Nature. Reproduced with permission.[3] Copyright 2016 WILEY-VCH. Reproduced with permission.[115] Copyright 2018, AAAS. Reproduced with permission.[91] Copyright 2021 Wiley-VCH. Reproduced with permission.[122] Copyright 2018, Springer Nature. Reproduced with permission.[201] Copyright 2021 WILEY-VCH. Reproduced with permission.[14] Copyright 2019 WILEY-VCH

pressure, vibrations and temperature (Figure 9A). The presented e-skin adopting the bionic interlocking structure can detect the pressure caused by the weak movement of human hair (0.6 Pa) and realize a temperature coefficient of resistance (2.93% $^\circ C-1$). They also showed the proof-of-concept applications of the e-skin in monitoring pulse pressure and temperature of the arterial blood vessel.

The contact interface between electronic skin and the monitoring sites of the human body may greatly affect sensing accuracy and diagnosis effect.[211–216] Choi et al.[208] presented a cephalopod-inspired suction cup as a dry adhesives for an ultrathin stretchable e-skin, which integrated with physiological sensors, drug delivery actuators and therapeutic nanoparticles (Figure 9B). The integrated e-skin is used to monitor vital signs and physical activities such as body temperature, respiration, pulse, blood pressure, and physiological tremor. The strong van der Waals force and negative pressure brought by the biomimetic suction cup structure can make the device fit closely to the human skin, which enhances the adhesion and comfort to the skin, and improves the sensitivity of biometrics measurement and the effect of transdermal drug delivery.

Biocompatible and adaptable, hydrogels can be used in a variety of applications. They are particularly good for perspiration analysis and human-machine interface. However, it is challenging to achieve high tensile and optimum sensitivity in hydrogel-based electronic devices at the same time. Inspired by fiber-reinforced microstructures and mechano-transduction systems of human muscles, Ge et al.[209] proposed a novel hydrogel with self-healing ability (90.8%) to realize strain and temperature sensing (Figure 9C). The bioinspired sensor exhibits good stretchability (about 991%), high sensitivity (with an 18.28 gauge factor and $-0.016\,^\circ C^{-1}$ thermosensation) and a wide strain detection range (about 268.9%). The bionic hydrogel device can recognize human speech and serve as a "heat indicator" to determine the temperature of the human forehead.

The detection of eye-related pathological signals and early diagnosis are of great significance in avoiding serious eye diseases.[217,218] Wang et al.[199,219,220] proposed a contact lens sensor to monitor changes in moisture and pressure, which is made of hydrogel-based on chameleon-inspired structural-color actuators (Figure 9D). The PHEMA hydrogel is water-rich network structured. It is very sensitive to

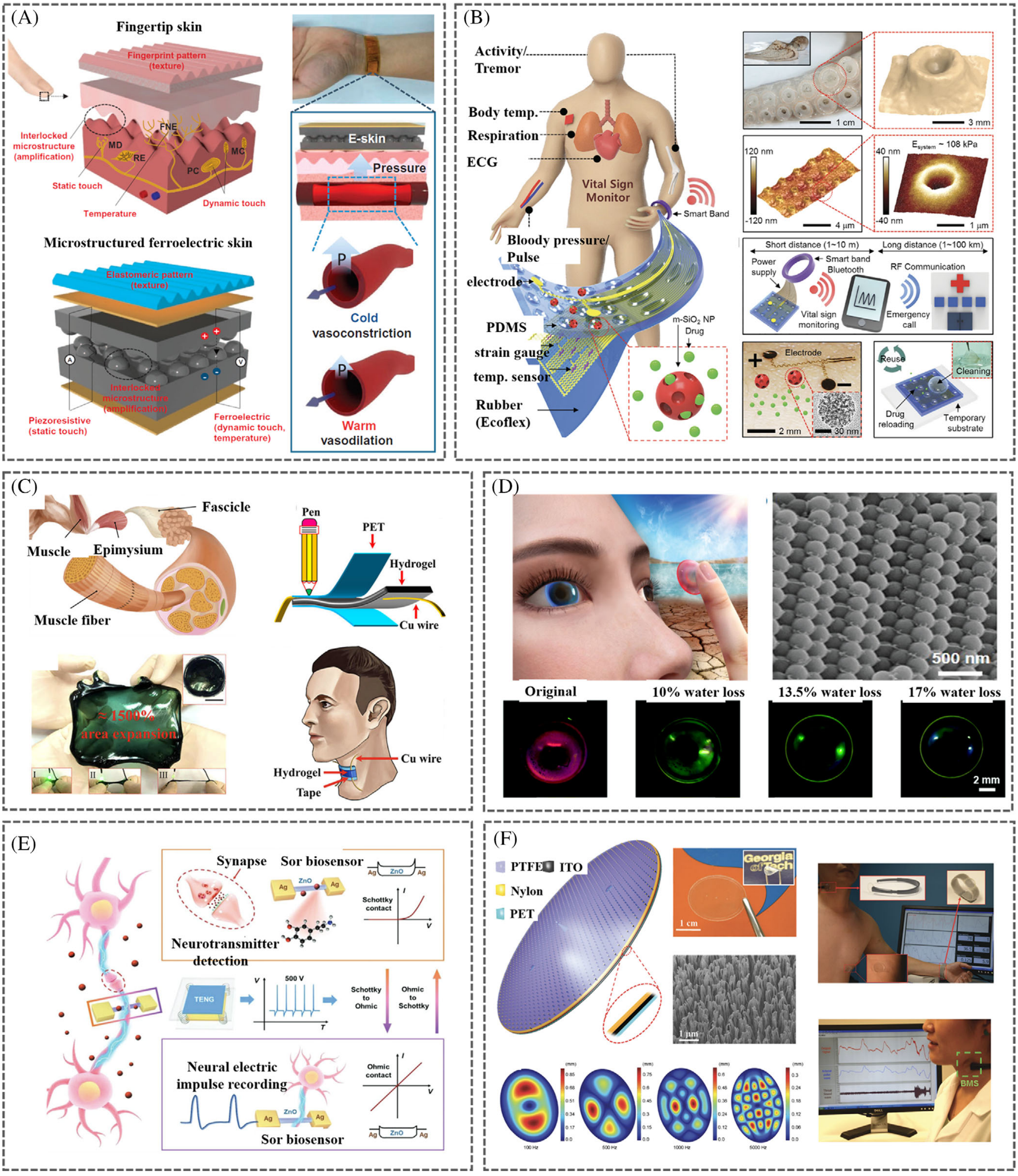

FIGURE 9 Bioinspired sensor systems for health care. (A) Ferroelectric skins inspired by fingertip microstructure. Reproduced with permission.[142] Copyright 2015, AAAS. (B) A smart medical skin inspired by cephalopod. Reproduced with permission.[208] Copyright 2015, WILEY-VCH. (C) A strain and temperature sensor with self-healing hydrogels inspired by muscle. Reproduced with permission.[209] Copyright 2019, American Chemical Society. (D) A lens sensor for ophthalmic health monitoring inspired by chameleon. Reproduced with permission.[199] Copyright 2020, The Royal Society of Chemistry. (E) Synapse-like biosensors based on reversible conversion between Schottky and Ohmic contacts. Reproduced with permission.[210] Copyright 2019, WILEY-VCH. (F) A self-powered eardrum-inspired sensor for cardiovascular system characterization and voice recognition. Reproduced with permission.[116] Copyright 2015, WILEY-VCH

changes in humidity and pressure, and can change the structural color by adjusting the refractive index and lattice spacing. The bionic contact lens sensor showed good biocompatibility and sensing ability, which has great prospects in eye monitoring.

The detection of neurotransmitters and nerve impulses in the physiological environment has significance for brain science and clinical diagnosis. Zhao et al.[210] proposed a bioinspired sensor similar to synapses, realizing the reversible conversion of Schottky and ohmic contacts based on TENG (Figure 9E). The high-output voltage of TENG can effectively reduce Schottky barrier height and achieve a high-sensitivity detection of dopamine (0.1 μmol ml^{-1}) in Schottky-contact state and neural electric impulse (0.2 V) in Ohmic-contact state.

Most wearable pressure sensors are now based on changes in capacitance, piezoelectricity, and resistivity caused by force. They respond poorly to some high-frequency vibrations, such as human voices. Drawn inspiration from the eardrum, Yang et al.[116] reported a bioinspired membrane sensor based on TENG (Figure 9F). The device exhibits a high sensitivity of 51 mV Pa $^{-1}$, a fast response time (< 6 ms), and a wide band for sensing (0.1–3.2 kHz), which can recognize human throat sounds at high frequencies, as well as detect low-frequency arterial pulses for real-time monitoring of human health.

Patients suffering from chronic wounds may experience severe pain. It's caused by the disruption of healing induced by a variety of pathophysiological causes, which are reflected in the composition of wound exudate.[221] Point-of-care wound monitoring can provide diagnosis and treatment information in real time.[222] Gao et al.[200] reported a multi-channel immunosensor system that can monitor numerous biomarkers at the same time. It is based on a bionic microfluidic wound exudate collector inspired by Texas horned lizard skin. The Texas horned lizard's skin has the ability to predict the direction of fluid flow under gravity. Inspired by this, a passive microfluidic collector for liquid directional transport was designed for guiding the wound fluids to the sensing area. The system is composed of an electrochemical sensor array that can track a number of indicators at the same time, such as inflammatory mediators, physicochemical parameters, and so on.

4.2 | Human-machine interaction

At present, portable, wearable devices affect all aspects of people's lives. Human-machine interaction can be found anytime and everywhere, such as intelligent identification and interactive control. As a part of the bionic tactile sensing closed-loop system, artificial haptic interfaces play an important role in human-machine interaction. Some recent works have focused on its application in the field of human-machine interaction, especially in virtual reality (VR) and augmented reality (AR).[223–226] Sensors can serve as the interface to gather the signals transmitted by human stimuli such as touch, sound, myoelectric activity, and nerve impulses for the front end of human-machine interaction system, and then transform them into the data input required by the back end.[227–231] The adoption of bioinspired sensor technology enables the further development of human-machine interaction. On the one hand, bioinspired sensor systems such as e-skin can improve the sensitivity and detectable range of the front end of the human-machine interaction system to receive external signals,[232] on the other hand, bioinspired sensor system such as artificial synapses can enhance the efficiency and accuracy of signal conversion at the interface.[233]

Artificial neural networks, which are inspired by biological nervous systems, can be used in biomedical interfaces such as artificial limbs and brain-machine interfaces.[234–237] Synapses are the regions of the brain where neurons communicate and functionally interact with one another. The artificial neural system is inspired by the process of synapses to transmit information, aims to establish a link between cells or tissues and devices.[238–240] Chen et al.[233] developed a piezotronics graphene artificial sensor synapse (Figure 10A). The piezoelectric nanogenerator can adjust the synapse weight through the spatiotemporal characteristics of external strain. The system includes sensing, transmission, and processing units and can be simply regarded as a sensory nervous system. Based on the electric double layer formed at the ion gel and graphene interface, piezoelectric potential can effectively replace gate voltage to regulate artificial synaptic devices. The self-powered system can achieve typical synaptic behaviors such as pulse enhancement/inhibition, weight adaptability, paired-pulse facilitation, and pulse weight dynamic adjustment as the interface of human-machine interaction. Keene et al.[241] presented a biohybrid synapse with neurotransmitter mediation, consisting of an organic neuromorphic device as postsynaptic domain and dopaminergic cells as presynaptic domain (Figure 10B). The dopamine secreted by the PC-12 cells at the presynaptic is oxidized on the postsynaptic gate electrode. The change in the charge state of the electrode causes the ion current in the electrolyte to change the conductivity of the postsynaptic channel, allowing the transmission of information. By simulating the circulation mechanism of dopamine, they paved the way for combining the biological neural network and the back end of the human-machine interaction system.

Biological neural systems are extremely efficient in dealing with distributed and parallel complex challenges

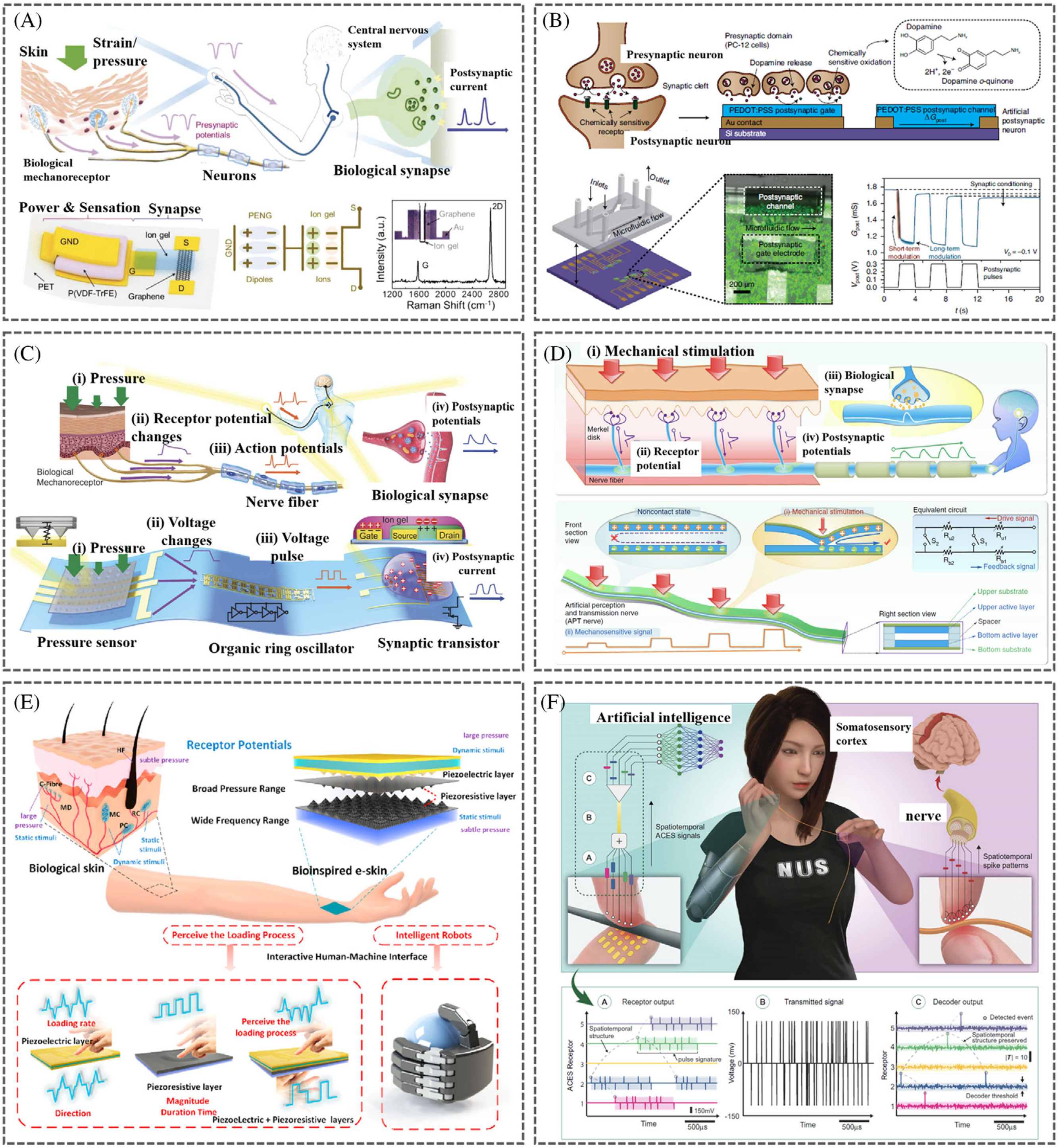

FIGURE 10 Bioinspired sensor systems for human-machine interaction. (A) A piezotronic sensory artificial synapse. Reproduced with permission.[233] Copyright 2019, WILEY-VCH. (B) A hybrid artificial synapse. Reproduced with permission.[241] Copyright 2020, Springer Nature. (C) A bioinspired afferent nerve. Reproduced with permission.[13] Copyright 2018, AAAS. (D) A bioinspired analogous nerve. Reproduced with permission.[242] Copyright 2020, Springer Nature. (E) A multifunctional dual-mode e-skin. Reproduced with permission.[243] Copyright 2020, Elsevier. (F) An artificial peripheral nervous system. Reproduced with permission.[15] Copyright 2019, AAAS

when compared to typical computational systems. Kim et al.[13] constructed an artificial afferent nerve with multiple sensing receptors (Figure 10C). Each pressure sensor corresponds to an artificial nerve fiber, which converts external force signals (1–80 kPa) into electrical impulses. The electrical impulses conducted by different artificial nerve fibers are integrated and converted into postsynaptic currents by transistors. The artificial afferent nerve and the cockroach's efferent nerve are connected to form a coupled electronic reflex arc to simulate reflex movement. The pressure signal of the touch sensor in the hybrid nervous system reaches the electronic neuron, and the electronic neuron converts the signal into a digital signal, which is transmitted to the synaptic transistor, and then to the biological efferent nerve of the detached cockroach leg, thereby driving the tibial extensor muscle. The coupled system has potential applications in neurorobotics and human-machine interaction.

The integration of numerous distributed functional units to imitate the operation of the organic sensory nervous system is common in bionic artificial devices, which leads to a complicated structure of connection and disrupted signal transmission. Liao et al.[242] demonstrated an integrated bioinspired artificial nervous system with the functions of sensing, recognizing and transmitting information based on a separate double-layers structure (Figure 10D). The researchers filled the hollow area of the paper substrate with graphite and form a graphite-based film as the conductive path, and then the conductive wire was led out on the long conductive axis through silver paint, which constitutes the basic part of APT nerve. They fixed two long strips of paper-based substrates deposited with conductive graphite films face-to-face, realizing an electrical double-layer micro-separation structure. Similar to the function of spinal cord interneurons, the specific structure allows it to recognize only one mechanical signal at a time. The presented artificial neural network has the characteristics of good flexibility, fast response (< 21 ms), and excellent stability (> 10 000 tests). In addition, the high resolution of the stimulus in different areas makes it have broad application prospects in human-machine interaction, such as intelligent recognition with the combination of different functional sensing materials.

The ability to detect static and dynamic mechanical stimuli simultaneously in a linear manner across a wide pressure range is critical for electronic skin in human-machine interaction. Designing dual-mode sensors is an effective approach to monitor different external stimuli at the same time. Qiu et al.[243] reported a biological skin-inspired sensor (Figure 10E), which was mainly composed of a piezoresistive layer and a piezoelectric layer with an interlocking structure. The 150-nm gold electrodes were evaporated on both sides of the piezoelectric membrane using an electron beam evaporator, then graphene oxide was coated on the piezoelectric layer of the pyramid structure. Finally, the piezoelectric layer and the piezoresistive layer were assembled layer by layer, and the PDMS was encapsulated on both sides to complete the fabrication of the device. Thanks to the coupling of piezoresistive effect and piezoelectric effect, this dual-mode sensor works in a broad pressure range (0.015–9 kPa) and wide frequency range (0–700 Hz) with high sensitivity (14.5 kPa^{-1} of piezoresistive mode and 1.62 V kPa^{-1} of piezoelectric mode). The dual-mode sensor was demonstrated for the first time as a smart manipulator in a factory to grasp and transport precision objects on an assembly line.

An ideal electronic skin should be as highly reactive as biological skin and consist of a large number of distributed flexible tactile sensors. Inspired by the nervous system, Lee et al.[15] developed a platform called Asynchronously Coded Electronic Skin (ACES) (Figure 10F), which can sense and transmit thermal and tactile information simultaneously with low-readout latencies. The e-skin consists of 240 sensing receptors and can transmit multiple signals to a receiver. In terms of response speed, the reaction time of asynchronous events is less than 60 ns and the temporal precision is stable at 1 ms. The ACES can achieve simple wiring and extraordinary sensitivity even when the number of sensors increases, which is the key feature that promotes the expansion of large-scale e-skin for use in intelligent robots, prosthetic devices, and other human-machine interfaces.

5 | CHALLENGES AND PROSPECTS

Nature is an inexhaustible source of inspiration for scientific research. With remarkable features like low-power consumption, ultra-sensitivity and self-adaptability, bioinspired sensor systems lead the development of new generation sensor technology. However, with the increasing popularity of personalized medicine, home health care, and human-machine interaction, there is a higher demand for the existing sensor systems. The current challenges of bioinspired sensor systems are as follows (Figure 11):

1. In-depth understanding of natural sensing mechanisms: It is still a challenge to figure out how to draw inspiration from natural sensory systems to guide the design of new types sensors. The most effective approach is a thorough understanding of natural principles and artificial reconstructing of biological sensing processes, which requires the integration of various fundamental disciplines, including biology, chemistry, physics, materials science, electronic engineering, computer science, and so forth. Bionic strategies may be more efficient through an interdisciplinary approach.[244]
2. Discovery of new bionic materials and structures: The continuous evolution of the natural sensory systems of different species over millions of years helps

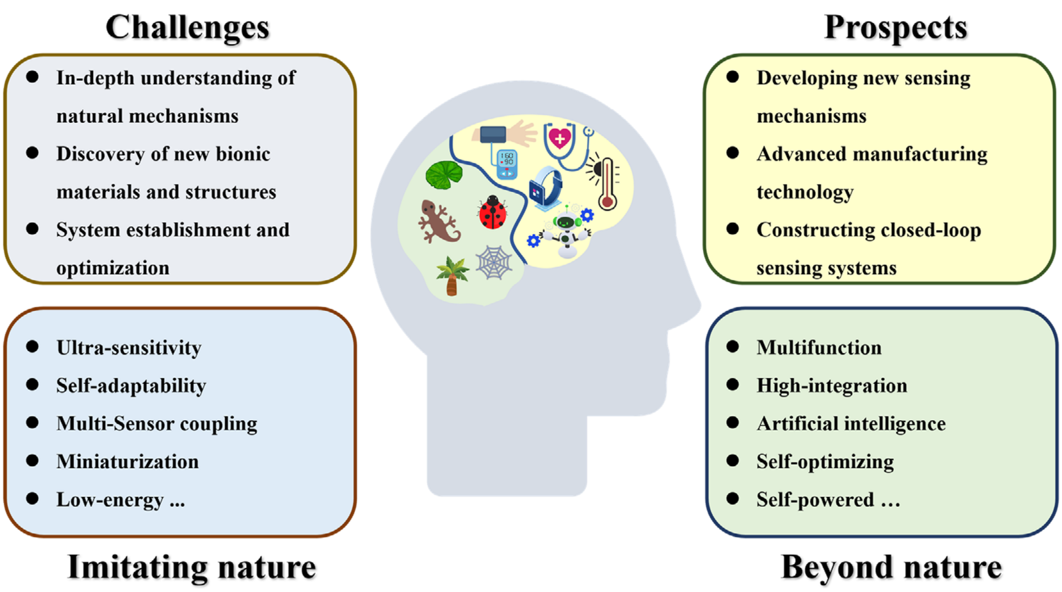

FIGURE 11 Challenges and prospects of bioinspired sensor systems

them survive in diverse environments. In addition to remarkable perception, natural sensory systems often have the properties of self-adaptability and low-power consumption, which derive from unique biological materials and structures. There is still a need to construct novel bionic materials and structures to improve the performance of the bioinspired sensor system after understanding the mechanism of natural sensory systems. The application of advanced manufacturing technology (such as 3D and 4D printing technology) and hybrid bionic strategies have enabled higher adaptability and programmability of the bioinspired sensor system.[2] With the continuous development of material technology and biomimetic technology, bioinspired sensor systems will achieve performance beyond the natural sensory system, such as self-optimizing and self-powered.

3. System establishment and optimization: Multiple sense organs in organisms work in parallel without mutual interfering, benefiting from their sophisticated closed-loop sensing system, which guarantee the accuracy of multiple complex signals from perception to feedback. Exploring the features and equivalent models of natural sensing closed-loop is of great importance for designing complex large-scale and multi-sensor coupled bioinspired sensor system. Specifically, bioinspired sensor systems still have much space for advancement compared to natural sensor systems, which are summarized as follow:

a. Computational capability: Most bioinspired sensor systems currently have relatively basic sensing and signal processing capabilities, limited to simple data recording and computations like threshold assessment and peak detection.[201] The existing computational capability of bioinspired sensor systems make it difficult to meet the needs for attitude perception, shape evaluation, and material recognition, among other things. Machine learning can mine data to discover inherent rules and representation levels in a sample dataset, which is an effective way to improve the computational capability of bioinspired sensor systems.
b. Integration: At present, combining intelligent algorithms like deep learning with bioinspired sensor system is still tricky. Storing vast volumes of data and reducing power consumption are critical challenges that must be addressed. Integrating other functional units such as processing units, wireless transceiver units and power management units is necessary for the efficient storage, analysis and transmission of vast amounts of sensing data. A highly integrated and versatile bioinspired sensor system is the future development trend.
c. Miniaturization: The connection of numerous functional components, especially when multi-sensing and vast-area sensing systems are required, would considerably increase the volume and complexity of the sensing system. Miniaturization is another critical issue that multifunctional bioinspired sensor systems need to solve urgently. With the significant progress of micro electro mechanical systems (MEMS) and micro-nano manufacturing technologies, bioinspired sensor system may be further miniaturized without compromising function.
d. Power management: The miniaturization of the entire system usually sacrifices the volume of the power

supply, limiting the service life and function of the sensor system. There are two approaches to address the power supply of bioinspired sensor systems. The first is to construct bioinspired sensor systems based on self-powered sensors such as triboelectric nanogenerators and piezoelectric nanogenerators, which can directly convert the variation of detection objects into sensing signals without an external power supply. Second, energy harvesting technology can be combined with bioinspired sensor system to convert the energy from the human body or environment into electricity for the entire system. For example, the thermoelectric generator based on the thermoelectric effect[245] can transform the temperature difference between the human body and the environment into electricity for electronic skin. Taking use of some emerging energy harvesting technologies such as solar cell, biofuel cell, hydrovoltaic effect generator, various energy sources from the environment like solar energy, chemical energy and vaporization energy can all be utilized to maintain the continuous operation of bioinspired sensor system.[246]

6 | CONCLUSION

Long-term natural selection and evolution have endowed organisms with many amazing capabilities, such as ultrasensitive senses and self-adaptability to environmental changes. Inspiration from natural organisms has effectively contributed to advancements in science and engineering to improve people's lives. Bioinspired sensor system possesses sensing performance rivaling nature and various bionic functionalities, which can help people better sense the environment and quantify themselves. This review focuses on the research progress of bioinspired sensor system in recent years. Three bionic strategies are defined according to different sources of bionic inspiration, including bionic materials, bionic structures, and functional bionic. Bioinspired sensor systems with different working mechanisms are summarized and classified. Some typical research works are introduced by the category of piezoresistive, capacitive, triboelectric, piezoelectric, and other types. For applications of bioinspired sensor system, here we concentrate on the applications of bioinspired sensor system in health care and human-machine interaction, which affect all aspects of people's lives. Human pulse, blood pressure, intraocular pressure, joint activity, body temperature, body fluid composition and other physiological information can be detected quantitatively through different type of bioinspired sensor systems, which is of great significance for the diagnosis and prevention of diseases. As two representative types of bioinspired sensor system, electronic skin and artificial neural systems play an important role in human-machine interaction, establishing a bridge between human and machine. Humans can express different kinds of information to machines more easily by e-skin, and machines can obtain human intentions more effectively by the artificial neural system.

The wisdom and diversity of biological sensory systems are enormous, and much remains unexplored. Bionic sensing technology will continuously inject rich inspirations into various fields such as industrial, medical, food safety, military and robotic, stimulating new vitality in their development. Bioinspired sensor system will have a promising future under the continuous in-depth understanding of natural mechanisms and exploring new biomimetic materials and structures. With the development of various interdisciplinary disciplines, integrating smart materials and artificial intelligence algorithms, bioinspired sensor system will ultimately achieve the performance and functions from imitating nature to surpassing nature.

ACKNOWLEDGMENTS

Jiangtao Xue and Yang Zou contributed equally to this work. This study was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (XDA16021101), National Natural Science Foundation of China (61875015, T2125003) and Beijing Natural Science Foundation (JQ20038).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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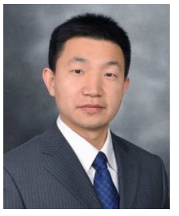

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How to cite this article: Xue J, Zou Y, Deng Y, Li Z. Bioinspired sensor system for health care and human-machine interaction. *EcoMat*. 2022;e12209. doi:10.1002/eom2.12209