nanoenergy advances

Review

Recent Progress of Bioinspired Triboelectric Nanogenerators for Electronic Skins and Human–Machine Interaction

Baosen Zhang [1,*], Yunchong Jiang [1], Baojin Chen [2], Haidong Li [1] and Yanchao Mao [2,*]

[1] Henan Engineering Technology Research Center of Energy Conversion and Storage Materials, College of Science, Henan University of Engineering, Zhengzhou 451191, China
[2] Key Laboratory of Materials Physics of Ministry of Education, School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001, China
* Correspondence: zhangbaosen20@mails.ucas.ac.cn (B.Z.); ymao@zzu.edu.cn (Y.M.)

Abstract: Advances in biomimetic triboelectric nanogenerators (TENGs) have significant implications for electronic skin (e-skin) and human–machine interaction (HMI). Emphasizing the need to mimic complex functionalities of natural systems, particularly human skin, TENGs leverage triboelectricity and electrostatic induction to bridge the gap in traditional electronic devices' responsiveness and adaptability. The exploration begins with an overview of TENGs' operational principles and modes, transitioning into structural and material biomimicry inspired by plant and animal models, proteins, fibers, and hydrogels. Key applications in tactile sensing, motion sensing, and intelligent control within e-skins and HMI systems are highlighted, showcasing TENGs' potential in revolutionizing wearable technologies and robotic systems. This review also addresses the challenges in performance enhancement, scalability, and system integration of TENGs. It points to future research directions, including optimizing energy conversion efficiency, discovering new materials, and employing micro-nanostructuring techniques for enhanced triboelectric charges and energy conversion. The scalability and cost-effectiveness of TENG production, pivotal for mainstream application, are discussed along with the need for versatile integration with various electronic systems. The review underlines the significance of making bioinspired TENGs more accessible and applicable in everyday technology, focusing on compatibility, user comfort, and durability. Conclusively, it underscores the role of bioinspired TENGs in advancing wearable technology and interactive systems, indicating a bright future for these innovations in practical applications.

Keywords: triboelectric nanogenerator; bionic; self-powered sensor; electronic skin; human–machine interface

Citation: Zhang, B.; Jiang, Y.; Chen, B.; Li, H.; Mao, Y. Recent Progress of Bioinspired Triboelectric Nanogenerators for Electronic Skins and Human–Machine Interaction. *Nanoenergy Adv.* **2024**, *4*, 45–69. https://doi.org/10.3390/nanoenergyadv4010003

Academic Editors: Christian Falconi and Dukhyun Choi

Received: 21 November 2023
Revised: 27 December 2023
Accepted: 11 January 2024
Published: 17 January 2024

1. Introduction

The field of human–machine interaction (HMI) and electronic skin (e-skin) has made remarkable strides, yet it is riddled with challenges that have hindered its progress [1–6]. The development of bionic triboelectric nanogenerators (TENGs) provides innovative opportunities for e-skin and HMI [7–13]. This innovation is primarily driven by the quest to replicate the complex and nuanced functionalities of natural systems, particularly those of human skin [14–19]. Traditional electronic devices often fall short in emulating the dynamic responsiveness and adaptability required for seamless integration with the human body [20–25]. Bioinspired TENGs, leveraging the principles of triboelectricity and electrostatic induction, emerge as a promising solution [26–30]. They offer the potential to closely mimic the natural tactile and sensory capabilities of biological systems, a pivotal step towards more intuitive and harmonious HMIs [31–36]. The inspiration from biological structures, such as the delicate texture of skin or the intricate patterns of plant surfaces, enables TENGs to interact with their environment in a more effective manner [37–41].

The shift towards biomimicry in the development of TENGs underscores a broader trend in technology: the harmonization of human-made devices with the principles of natural design [42–47]. The rigidity and limited sensitivity of conventional electronic materials often hinder their application in areas requiring flexibility and high tactile responsiveness, such as wearable electronics and interactive interfaces [48–51]. Bioinspired TENGs provide a novel approach by emulating the properties of living organisms, which have evolved to efficiently interact with and adapt to their surroundings [52–54]. This biomimetic strategy enables TENGs to achieve enhanced sensitivity and flexibility, essential for the next generation of e-skins [55–57]. Furthermore, the self-powering nature of TENGs, derived from natural energy conversion processes, presents a sustainable solution to the challenges of energy supply in wearable devices, marking a significant stride towards long-term autonomous electronic interfaces.

This review aims to provide a comprehensive exploration of the recent advancements in bioinspired TENGs, particularly focusing on their application in e-skins and HMI (Figure 1). The review begins with an introduction to TENGs, discussing their basic principles and four operational modes. It then delves into the realm of structural biomimicry, exploring TENGs inspired by both plant and animal models. Following this, the review examines material biomimicry in TENGs, highlighting developments in protein, fiber, and hydrogel-based designs. The primary focus is on the innovative applications of these bioinspired TENGs in tactile sensing, motion sensing, and intelligent control within e-skins and HMI systems. The review also addresses the challenges and future prospects of TENGs, exploring avenues for performance enhancement, large-scale fabrication, and system integration. By offering an in-depth analysis of these developments, the review seeks to provide insights into the current state and future potential of bioinspired TENGs, contributing to the advancement of wearable technology and interactive systems.

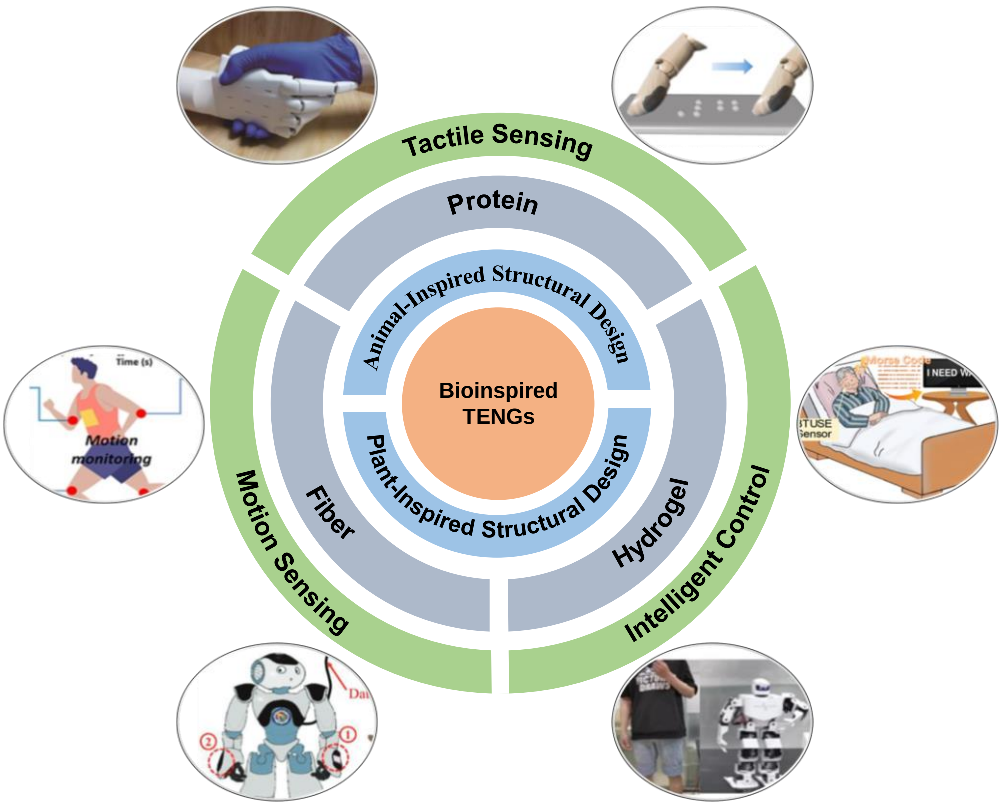

Figure 1. A general description of bionic TENG in E-skin and HMI. Reprinted with permission from Ref. [26]. Copyright 2020, Wiley. Reprinted with permission from Ref. [58]. Copyright 2022, Wiley. Reprinted with permission from Ref. [59]. Copyright 2021, Wiley. Reprinted with permission from Ref. [60]. Copyright 2023, Elsevier. Reprinted with permission from Ref. [61]. Copyright 2021, Elsevier. Reprinted with permission from Ref. [62]. Copyright 2022, American Chemical Society.

2. Four Distinct Working Modes of TENGs

Bionic TENGs, epitomizing the confluence of bioinspired design and nanotechnology, have emerged as pivotal components in the realm of energy harvesting and sensor technology (Figure 2) [63,64]. Their intrinsic ability to convert mechanical energy into electrical signals through distinct operational modalities renders them exceptionally conducive for applications in HMI and e-skin, signifying a paradigm shift in the interface between humans and machines. The vertical contact-separation mode of TENGs exemplifies a direct and effective mechanism for energy conversion [65–67]. This mode operates on the fundamental principle of creating and disrupting contact between two triboelectrically disparate materials. Each contact and subsequent separation event induces a transfer of charges, resulting in a measurable electrical output. This mode's responsiveness to compressive forces renders it particularly suitable for HMI applications where direct physical interaction is involved. The integration of such TENGs in interactive touch panels or tactile sensors can facilitate a more nuanced and responsive control mechanism, allowing for a more precise and efficient human–machine interface. In the lateral sliding mode, TENGs exploit the relative tangential motion between two triboelectric layers [68–70]. This mode is adept at translating lateral mechanical motions into electrical energy, effectively capturing the dynamics of shear forces. The application of this mode in HMI is profound, particularly in developing interfaces that can interpret and respond to complex gestures and movements. This mode's sensitivity to directional nuances enhances the capability of machines to interpret human intent with greater fidelity, thus fostering a more seamless and intuitive interaction between humans and technology. The single-electrode mode, characterized by its simplistic yet effective design, involves a single electrode in conjunction with a triboelectric material [71–73]. The electrical output in this mode is governed by the variations in the electric field due to the proximity or movement of an object, often the human body or its appendages. This mode's capability to detect and respond to non-contact interactions makes it an invaluable asset in advancing HMI technologies, especially in contexts where contactless control is paramount, such as in sterile environments or in scenarios requiring gesture-based inputs. Lastly, the freestanding triboelectric-layer mode demonstrates a high degree of sensitivity and adaptability, facilitated by a movable triboelectric layer situated between two electrodes [73–75]. The motion of this layer, modulated by external stimuli, generates an electrical response. The implementation of this mode in e-skin applications is particularly promising. It enables the development of highly sensitive artificial skins capable of detecting a wide array of stimuli, from pressure gradients to textural variations. Such e-skins have profound implications in robotics and prosthetics, offering enhanced tactile feedback and situational awareness, thus bridging the gap between artificial systems and the nuanced complexities of human tactile perception. In essence, the four fundamental operational modes of bionic TENG–vertical contact-separation, lateral sliding, single-electrode, and freestanding triboelectric-layer—represent a significant advancement in the field of energy harvesting and sensory technology. Their integration into HMI and e-skin applications not only signifies an evolution in the way humans interact with machines but also heralds a new era of bioinspired, energy-efficient, and highly sensitive interface technologies. These developments promise to substantially enhance the symbiosis between humans and machines, fostering a future where interaction is not merely functional but also intuitive and adaptive.

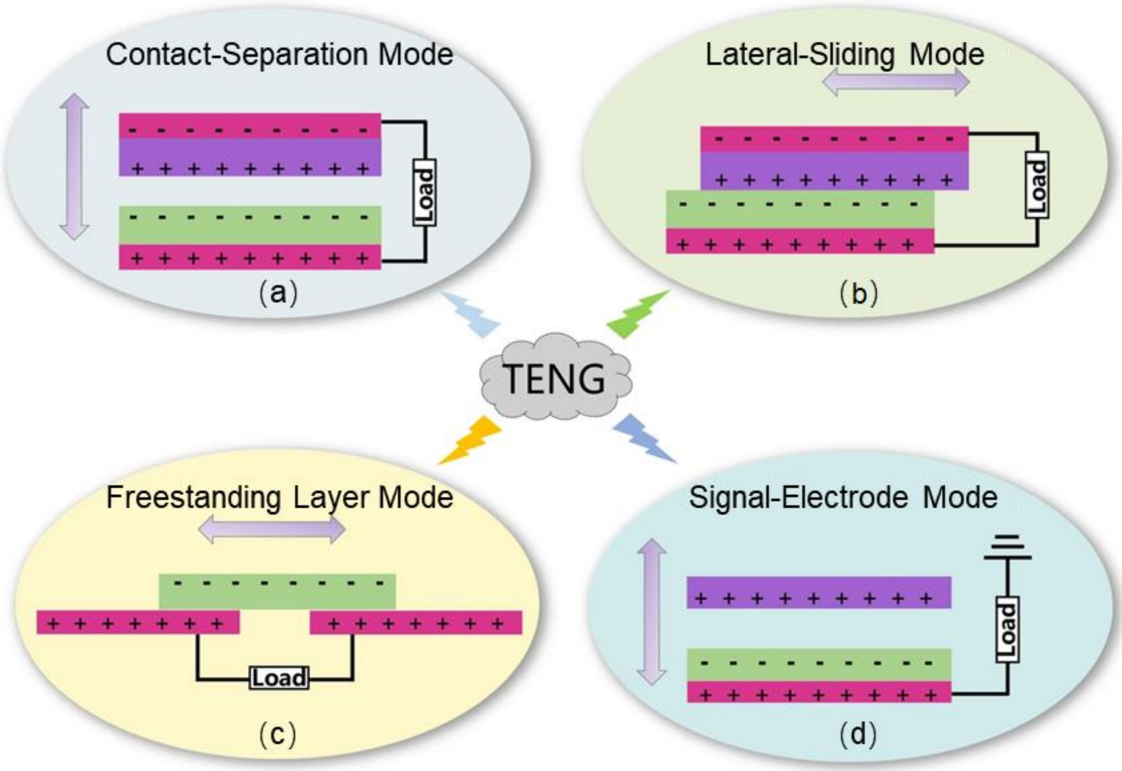

Figure 2. TENGs have four distinct working modes. Reprinted with permission from Ref. [63]. Copyright 2022, Springer. (**a**) Contact-separation mode (CS) [65–67]. (**b**) Lateral sliding mode (LS) [68–70]. (**c**) Freestanding triboelectric-layer mode (FT) [73–75]. (**d**) Single-electrode mode (SE) [71–73].

3. Structurally Biomimetic TENGs

In the burgeoning field of energy harvesting, structurally bionic TENGs represent a remarkable fusion of Bioinspired engineering and nanotechnology. These TENGs, divided primarily into plant bionic and animal bionic categories, harness the innate properties and structures found in nature to enhance their efficiency and adaptability. Plant bionic TENGs draw inspiration from the intricate designs and patterns observed in various flora, such as the microstructures of leaves or the vascular networks of plants. These natural templates are replicated at the nanoscale to create surfaces that maximize triboelectric effects, leading to improved energy conversion efficiencies. Animal bionic TENGs, on the other hand, emulate the textures, shapes, and functionalities of animal tissues or organs. Mimicking the skin, fur, or even the biomechanical movements of animals, these TENGs are designed to effectively capture and convert mechanical energy from movements or environmental interactions that are characteristic of the animal kingdom. This biomimetic approach not only broadens the applicability of TENGs across diverse environments but also opens new avenues for designing energy harvesters that are highly efficient, sustainable, and seamlessly integrated into various applications. A detailed comparison of structurally biomimetic TENGs is shown in Table 1.

Table 1. Summary of structurally biomimetic TENGs.

Devices	Working Mode	Bionic Objects	Q_{SC}	I_{SC}	V_{OC} (V)	Reference
bTENG	SE	lotus-leaf	-	-	1.2	[76]
TENG e-skin	CS	alathea zebrine leaf	23.98 μC/m^2	6.29 nA	3.14	[26]
TENG	CS	nature frond leaf	-	0.45 μA	78	[36]
PBHS	CS	nymphaea tetragona	-	46 nA	13.1	[77]
BAA	SE	cockroaches' antennae	35 nC	118 nA	55	[58]
SBA	SE	insect antennae	-	-	1.75	[71]
BSK-TENG	SE	imbricate scales	-	-	-	[78]
FSL-TENG	SE	fish-scale	-	6.2 μA	63	[68]
VCS-TENG	CS	shark skin	-	0.7 μA	32	[30]
BTUSE	CS	frog	-	-	0.7	[59]

3.1. Plant-Inspired Structural Design

Zhang and colleagues have pioneered the development of a biomimetic TENG (bTENG) and innovatively designed motion sensor (Figure 3a) [76]. This device is adept at detecting subtle mechanical disturbances, overcoming a significant limitation of conventional self-powered motion sensors in wake-up circuits that necessitate substantial pressure for activation. The bTENG's design is inspired by botanical structures, notably featuring leaf-like tendrils that augment its electrical output by a factor of four. This enhancement substantially broadens the detection range of the wake-up circuits. The distinctive structure of the bTENG, as depicted in Figure 3a, comprises a base plane adorned with an array of flat leaf-shaped tendrils. These flat leaf-shaped tendrils, affixed to the internal metal plate, effectively enlarge the contact area in three dimensions, culminating in increased electrical output. The tendrils are structurally composed of internal vein-like metal wires and an external leaf-shaped silicone rubber layer. This combination endows the bTENG with optimal mechanical properties, including high mechanical strength, stiffness, and pliability, essential for efficient performance and durability in various applications.

Guo et al. have made significant advancements in the field of robotic tactile sensing by developing a self-powered e-skin sensor utilizing a biomimetic TENG (Figure 3b) [26]. This sensor's design involves replicating the conical microstructure array of Calathea zebrine leaves, achieving a uniform conical shape on two frictional layers of polydimethylsiloxane (PDMS). The process entails a two-step molding technique: the initial step involves creating a reverse pattern of the C. zebrine leaf on PDMS, followed by a second molding to replicate the conical array on the PDMS substrate. These microcones, with an average height of approximately 25.7 μm, a base diameter of around 25.4 μm, and an average spacing of about 33.6 μm, form interlocking structures under pressure, enhancing the frictional area between the layers. This innovative replication method allows for the easy creation of the TENG's unique frictional layer structure. Furthermore, the incorporation of polytetrafluoroethylene (PTFE) microfibers on these layers significantly increases the pressure measurement sensitivity by up to 14 times. The flexibility of this self-powered TENG e-skin sensor facilitates its easy integration onto bionic hands, demonstrating its potential for robotic applications. This research marks a pivotal step in the development of advanced tactile sensors for robotics, combining biomimicry and nanotechnology for enhanced sensory capabilities.

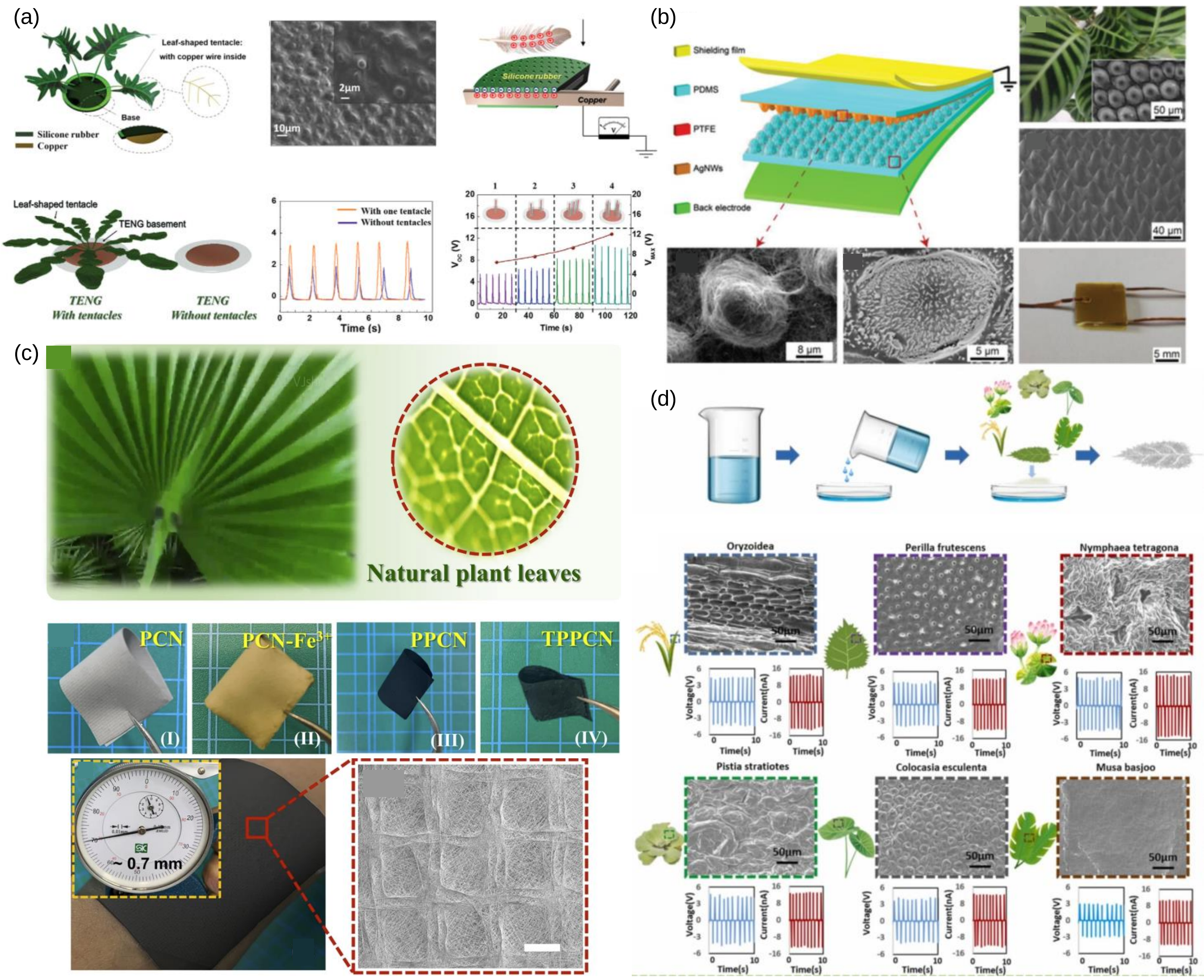

Figure 3. Plant bionic TENG. (**a**) Biomimetic TENG with micro-/nanostructure that imitates the nanostructure of leaves. Reprinted with permission from Ref. [76]. Copyright 2020, Wiley. (**b**) A TENG that replicates the surface microstructure of C. zebrine leaves. Reprinted with permission from Ref. [26]. Copyright 2020, Wiley. (**c**) Leaf-meridian Bioinspired nanofibrous electronics. Reprinted with permission from Ref. [36]. Copyright 2022, Springer Nature. (**d**) Plant-inspired and flexible hybrid self-powered sensors. Reprinted with permission from Ref. [77]. Copyright 2022, Elsevier.

Wang and their team, inspired by the frond leaf's natural structure, successfully developed a spatial multi-level nanofibrous membrane with a grid-like microstructure [36]. The fabrication process involved the use of a metal mesh template, in situ polymerization, and ultrasonic treatment to modify the surface of grid-like polyurethane (PU) nanofibers with carboxylated carbon nanotubes (CCNTs) and poly(3,4-ethylenedioxythiophene) (PEDOT). The resultant nanofibrous membrane exhibited remarkable properties, including high sensitivities of 5.13 kPa^{-1}, rapid response and recovery times (80 ms and 120 ms, respectively), and an ultralow detection limit of 1 Pa. Additionally, this membrane demonstrated versatility and scalability as a platform for multifunctional applications, such as electro-thermal conversion and energy harvesting. These findings suggest significant potential for the application of this biomimetic technology in next-generation wearable devices, offering a novel approach to high-sensitivity sensor.

A plant biomimetic and flexible hybrid self-powered sensor (PBHS) designed for motion spasm recognition was reported by Wang and colleagues (Figure 3d) [77]. The PBHS is uniquely structured. These surface patterns, inspired by the Victoria amazonica leaf, are created using soft lithography transfer molding, resulting in crystalline sizes ranging from several hundred nanometers to a few micrometers. The central layer of the sensor features layered PVDF-TrFE Nanofiber (LPPN) sensors. These sensors are designed by dropping approximately 2500 PVDF-TrFE piezoelectric polymers on a FPCB, measuring 108 mm by 12 mm, using near-field electrospinning (NFES). The nano-microfibers (NMF) encapsulating these polymers contribute to the sensor's enhanced energy harvesting capabilities. This innovative PBHS integrates the biomimetic PDMS TENG with the LPPN sensors on the FPCB substrate. The 2.2 mm thick wall of LPPN, predominantly consisting of piezoelectric polymers, significantly boosts the energy collection properties of the sensor. Remarkably, compared to the original PVDF-TrFE nanogenerator, the voltage of this hybrid sensor almost reaches 5 V, representing an approximately 200% increase. This advancement in the design and functionality of PBHS indicates a significant step forward in developing efficient self-powered sensors for biomedical applications.

3.2. Animal-Inspired Structural Design

In the innovative design of the bionic-antennae-array (BAA) sensor, Wang and colleagues have creatively utilized the concept of biomimicry, particularly drawing inspiration from the highly sensitive antennae of cockroaches (Figure 4a) [58]. The central feature of this biomimetic design is the implementation of an array of conductive fibers, meticulously arranged on the sensor's surface to mimic the functionality of cockroach antennae. These fibers, integral to the sensor's design, are not merely structural elements but are carefully engineered to enhance the sensor's electrostatic capabilities. The fibers are coated with silver nanoparticles, achieved through a novel synthesis process. This coating is not random but is strategically applied to maximize the electrostatic balance and sensitivity of the sensor, thereby replicating the natural mechanism of a cockroach's antennae which relies on static electrical fields for environmental sensing. The fabrication of the polyamide and Ag fibers, forming the core of the BAA sensor's antennae array, is a key aspect of the biomimetic design. The precise control over the fiber's morphology and the distribution of silver nanoparticles on their surface are crucial for the effective functioning of the sensor. This meticulous design ensures that the fibers can accurately detect noncontact motion, similar to how a cockroach's antennae perceive nearby objects through changes in the electrostatic field. The sensor's design not only captures the structural essence of cockroach antennae but also emulates their functional attributes. The arrangement and composition of the fibers are optimized to detect variations in electrostatic fields caused by approaching objects, thereby enabling the sensor to recognize motion with high sensitivity and resolution.

Inspired by the structure and function of insect antennae, Zhu et al. developed a self-powered bionic antenna (SBA) to enhance robotic tactile sensing (Figure 4b) [71]. This bionic sensor is particularly tailored for integration with micro-robots, which require sensors that are ultra-sensitive, lightweight, and capable of both passive and active real-time sensing. The SBA's design is a testament to the effectiveness of biomimicry in engineering. It comprises a two-stage actuator, mimicking the movement of insect antennae, which allows for active sensing in both horizontal and vertical planes. This feature endows the SBA with a unique capability to actively interact with its environment, much like the multifunctional antennae of insects that detect mechanical, odor, temperature, and humidity changes. This component is sensitive to different contact materials, much like the diverse receptors found in insect flagellum. The bionic design also integrates muscle fibers, akin to those driving the antennae of insects, thus providing the SBA with the ability to move and sense in a manner similar to its natural counterparts. This biomimetic approach in the SBA design not only captures the structural essence of insect antennae but also successfully replicates their functional attributes, highlighting the potential of biomimicry in developing innovative solutions for robotic tactile systems.

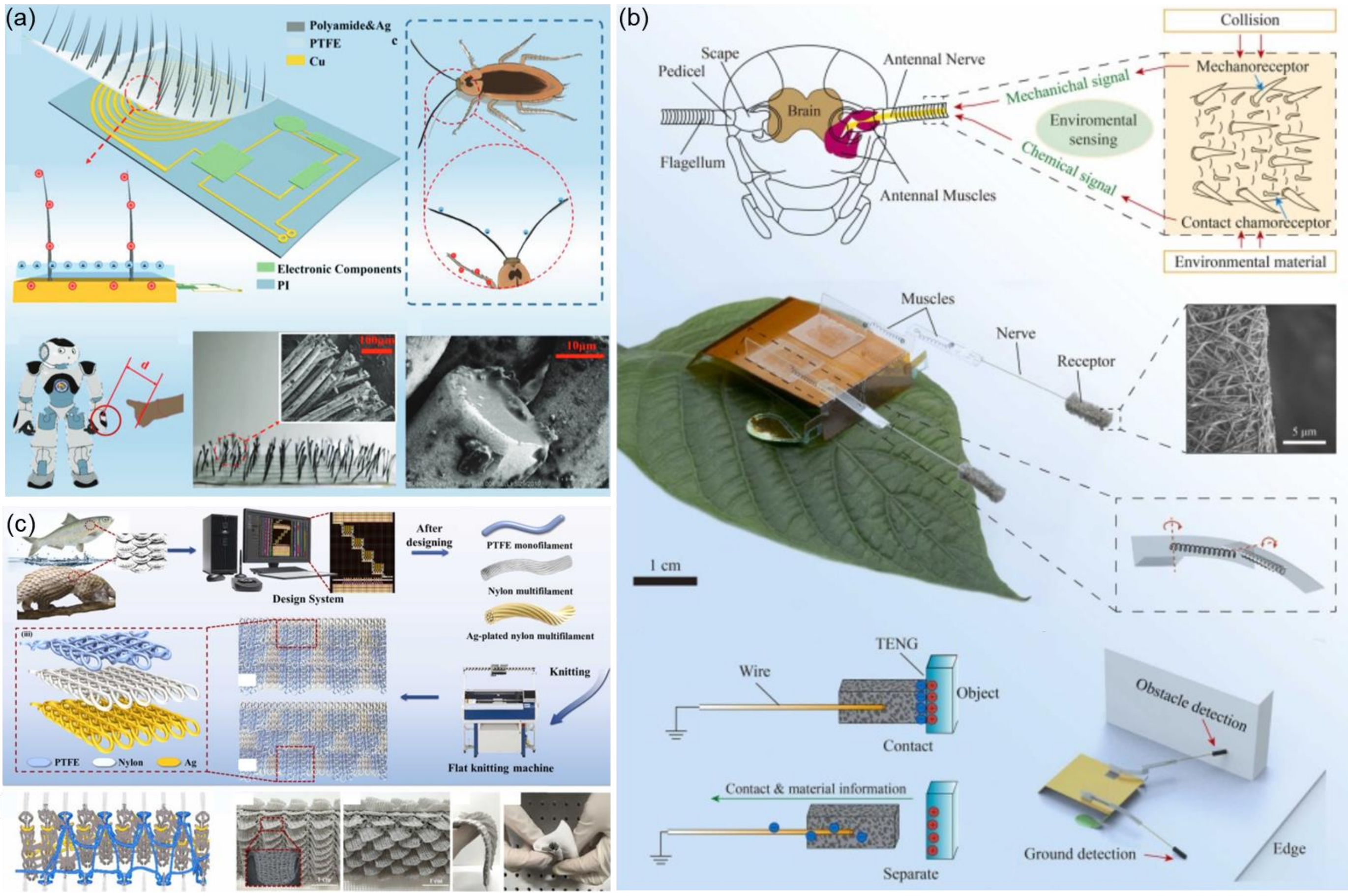

Figure 4. TENG inspired by animal structures. (**a**) TENG inspired by cockroach tentacles. Reprinted with permission from Ref. [58]. Copyright 2022, Wiley. (**b**) TENG inspired by insect tentacles. Reprinted with permission from Ref. [71]. Copyright 2023, Elsevier. (**c**) Scale bionic TENG. Reprinted with permission from Ref. [78]. Copyright 2022, Elsevier.

Niu et al. present the innovative design and fabrication of a bionic scales knitting triboelectric generator (BSK-TENG), inspired by nature's solutions to balancing protection and flexibility (Figure 4c) [78]. Drawing from the imbricate scale structures of creatures like snakes, fish, and pangolins, the BSK-TENG integrates bionic scales with a knitted structure, addressing the challenge of integrating intelligent and complex bionic structures into fabrics without compromising their inherent flexibility, comfort, and breathability. The design process involves a novel high-speed V-bed flat knitting fully-formed technology, enabling the creation of this multifunctional wearable fabric. This technique allows for the rapid and eco-friendly production of the BSK-TENG, suitable for mass production and commercial applications. The resulting fabric boasts a distinctive 3D hierarchical structure, effective for harvesting both water-drop and biomechanical energy in outdoor environments. Notably, the BSK-TENG exhibits anisotropic properties when bent, making it suitable for joint support and protection in outdoor sports.

Ma et al. introduce a novel biomimetic fish-scale-like TENG (FSL-TENG), inspired by the structure of fish scales (Figure 5a) [68]. This device leverages the unique properties of fish scales to harvest energy from both rotational and sliding motions in any direction without an off state. The FSL-TENG is fabricated using PET film and PTFE sheets, structured to imitate fish scales. This design entails a periodic symmetrical arrangement of electrodes and a curvilinear shape on each side, allowing for the capture of mechanical energy from diverse movements. The FSL-TENG's electrodes are modeled after the scales of the giant arapaima fish, which are known for their efficient energy dispersal and protection capabilities. The research demonstrates that the FSL-TENG, when oriented at an angle of 45°, achieves its peak output in terms of current, voltage, and power. This optimal performance is attributed to the maximum overlap area between the PTFE slider and electrodes at this specific angle. The device's adaptability is further enhanced by its lightweight and flexible nature, thanks to the PET film packaging, making it suitable for various applications.

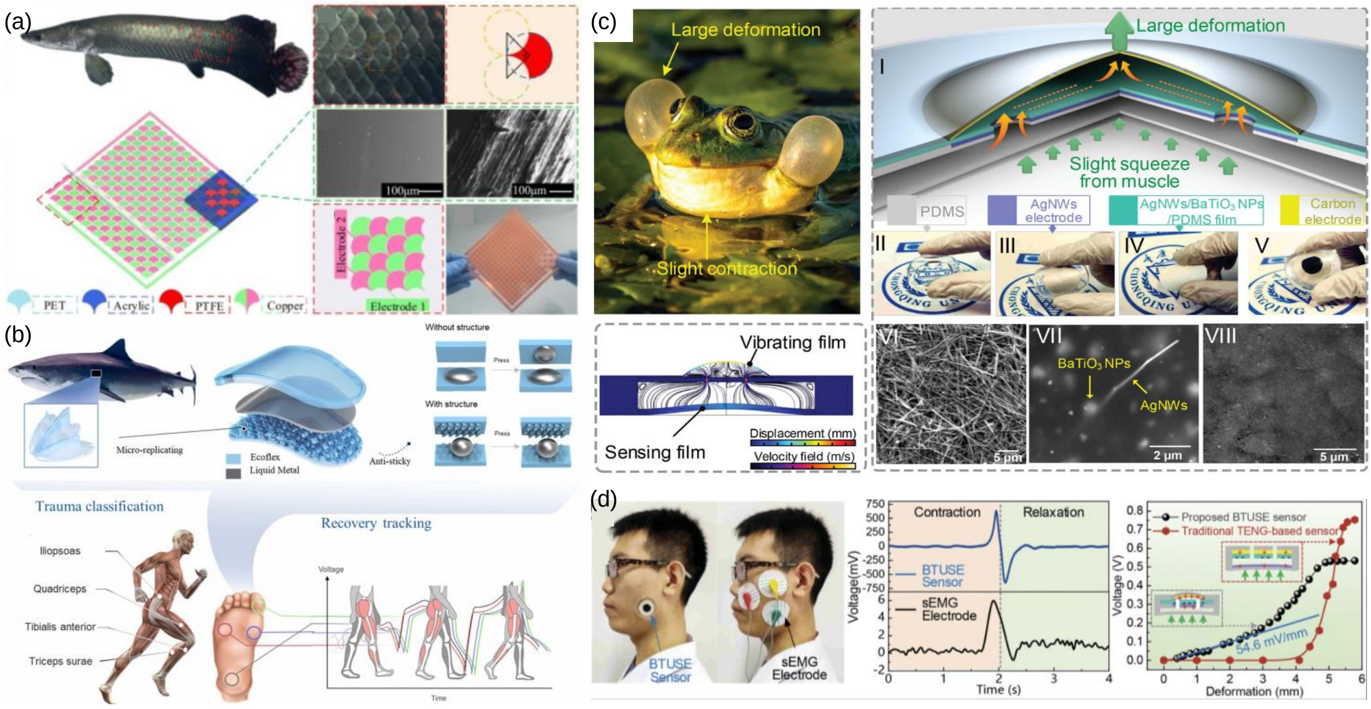

Figure 5. TENG inspired by animal structures. (**a**) Fish scale bionic TENG. Reprinted with permission from Ref. [68]. Copyright 2022, Elsevier. (**b**) Liquid metal TENG inspired by bionic shark skin. Reprinted with permission from Ref. [30]. Copyright 2022, Elsevier. (**c**,**d**) A TENG inspired by frog calls. Reprinted with permission from Ref. [59]. Copyright 2021, Wiley.

A wearable sensor for gait analysis is developed by Yeh et al., drawing inspiration from the unique microstructure of shark skin (Figure 5b) [30]. This biomimetic approach utilizes a solid–liquid TENG design, which incorporates a liquid metal encapsulated within a shark skin-like microstructure embedded on an Ecoflex surface. The key innovation lies in mimicking the hydrophobic and microstructured surface of shark skin, which significantly enhances the sensor's performance in terms of sensitivity and long-term stability. The sensor's design is grounded in the understanding of shark skin's natural properties, notably its rib-like microstructure that reduces flow resistance and minimizes liquid adhesion. This feature is crucial for preventing liquid metal adhesion during the sensor's operation, ensuring efficient signal monitoring and stability over prolonged use. The Ecoflex material, known for its flexibility and biocompatibility, is engineered to replicate the shark skin's microstructure, achieving a surface that is not only hydrophobic but also capable of self-cleaning, much like the lotus leaf effect. This Bioinspired sensor operates on a self-powered mechanism. The combination of the liquid metal and the Ecoflex surface with a shark skin-like microstructure results in a high charge transfer capability, vital for precise gait analysis. The sensor's efficacy is validated through a series of tests that demonstrate its ability to monitor various gait patterns, distinguishing between the walking patterns of healthy individuals and those with specific muscle injuries.

Zhou et al. introduce a bionic TENG-based sensor inspired by the croaking behavior of frogs, providing a novel approach for developing human–machine interfaces (HMI) for disabled individuals (Figure 5c) [59]. This sensor integrates TENG technology with a biomimetic design to effectively capture the micromotions of muscles, particularly the masseter muscle. The design of the sensor mimics the way a frog's mouth and vocal sac work in unison during croaking. When a frog croaks, the slight contraction of its mouth muscles causes a significant deformation in its external vocal sac, amplifying the sound. Similarly, the sensor consists of a sensing film and a deformable vibrating film made of flexible PDMS elastomer. This setup amplifies the minute muscle movements (micromotion) into substantial motion of the vibrating film. The sensor's high signal intensity (±700 mV) and wide sensing range (0–5 mm) offer a significant improvement over traditional biopotential electromyography methods, with a signal intensity 206 times higher (Figure 5d).

4. Material Biomimetic TENGs

In the interdisciplinary domain of energy harvesting, material bionic TENGs stand out as a testament to the innovative blending of material science and bioinspired engineering. These TENGs are primarily categorized into three distinct groups: collagen-based, bionic fiber, and hydrogel TENGs, each leveraging unique material properties to optimize energy conversion. Collagen-based TENGs utilize the structural and electrical properties of collagen, a fundamental protein in animal connective tissues, to create flexible and biocompatible energy harvesters. These devices mimic the natural resilience and adaptability of collagen, making them ideal for wearable and implantable energy applications. Bionic fiber TENGs, on the other hand, draw inspiration from the structural and functional aspects of natural fibers. By replicating the microstructures and mechanical properties of fibers found in nature, these TENGs achieve a remarkable balance between durability and flexibility, which is crucial for applications that require robust yet conformable energy harvesting mechanisms. Lastly, hydrogel-based TENGs capitalize on the hydrophilic nature and soft gel-like consistency of hydrogels. These TENGs emulate the moisture-retaining and soft characteristics of natural hydrogels, lending them unique advantages in terms of biocompatibility and flexibility. This category is particularly promising for applications in moist or aquatic environments and for integration with biological systems. Table 2 shows a detailed comparison of recent material biomimetic TENGs. Together, these material bionic TENGs not only push the boundaries of energy harvesting efficiency but also pave the way for more sustainable and environmentally harmonious energy solutions.

Table 2. Summary of material biomimetic TENGs.

Devices	Working Mode	Bionic Objects	Q_{SC}	I_{SC}	V_{OC} (V)	Reference
B-skin	SE	bovine serum albumin	-	0.7 µA	474	[79]
PCOBE-TENG	SE	achilles tendon of Simmental cattle	50 nC	5 µA	80	[60]
LMFG-TENG	CS	fish gelatin	-	0.8 µA	300	[80]
EG-skin	SE	silk protein	-	-	5	[81]
UVE-TENG	FT	fibrous membrane	-	1 µA	8k	[82]
DMWES	SE	fibrous	49 nC	1.6 µA	62	[11]
PTES	CS	eggshell membrane	-	-	-	[9]
organohydrogel TENG	SE	urea and glucose	26.9 nC	0.73 µA	83.9	[83]

4.1. Protein Material Bionics

Leng et al. focus on the development of a protein-based bioprotonic hydrogel (PBH), designed as a bioprotonic skin (B-skin) for artificial skin applications (Figure 6a) [79]. The fabrication process of the B-skin is inspired by the sebum membrane of human skin, specifically utilizing bovine serum albumin for its natural proton conductivity and glycerol, which is naturally present on human skin, to retain water. This mixture was stirred to form a clear solution. Then, 0.48 mL of 2-mercaptoethanol was added, causing the solution to become cloudy. Continuous stirring was resumed until the addition of 0.44 mL each of ethylenediamine (EDA) and ethanol, which once again clarified the solution. This final solution was cast onto a glass plate and left for 5 h to allow solvent evaporation, resulting in the formation of a bulk film. This film was then thoroughly washed with deionized water multiple times. The final step in the fabrication process involves immersing the film in glycerol for varying durations to produce different versions of PBHs. The B-skin exhibits several key properties: it is stretchable, anti-freezing, transparent, and biodegradable. Its stretchability allows it to extend to 400% without fracturing. The inclusion of glycerol not only aids in water retention but also endows the B-skin with anti-freezing properties, allowing it to remain flexible at temperatures as low as −20 °C. The B-skin's transparency, with a light transmittance of 93% in the visible region, and its biodegradability further enhance its suitability for on-skin applications.

Song et al. present a collagen-based conductive hydrogels (Figure 6b). In the evolving field of bioinspired e-skins and HMI, a groundbreaking study has made significant strides using collagen-based conductive hydrogels. The research focused on overcoming existing challenges in collagen-based hydrogels, such as balancing mechanical stability with self-healing, enhancing environmental adaptability, and integrating multifunctionality with diverse data acquisition channels. Utilizing collagen, oxidized hyaluronic acid, acrylic acid, and Zr^{4+} ions as primary materials, the study ingeniously constructed a double network with multiple dynamic covalent linking. The addition of ethylene glycol and silver nanoparticles resulted in a collagen-based conductive organohydrogel that simultaneously improved mechanical properties and self-healing capabilities, while also exhibiting excellent environmental stability and multifunctional attributes like transparency, antibacterial activity, and biocompatibility.

In Figure 6c, a leaf microstructure-inspired fish gelatin-based TENG (LMFG-TENG) is developed by Shi et al., harnessing the biodegradable and eco-friendly properties of fish gelatin (FG) [80]. This FG is derived from fish scales, treated to eliminate impurities and minerals, and then hydrolyzed to form a versatile FG solution, crucial for the film's triboelectric characteristics. The unique aspect of this study is the utilization of natural leaf patterns, such as those from lotus, Fatsia japonica, photinia serrulata, and ginkgo, to create molds for imparting diverse microstructures onto the FG films. These films are produced by pouring the FG solution onto the leaf-patterned molds and allowing it to dry, resulting in FG films with distinct leaf-inspired microstructures. The LMFG-TENG is assembled using these films. It is constructed by attaching copper foil to the FG films as electrodes, with a sponge layer serving as a spacer to facilitate contact-separation motion. The FG films exhibit significant biodegradability, dissolving in water within minutes and degrading naturally in soil, underscoring the device's environmental sustainability. The LMFG-TENG's efficiency is further enhanced by optimizing operating parameters and film size and thickness, with the lotus leaf-inspired microstructure emerging as the most effective, leading to a maximum voltage.

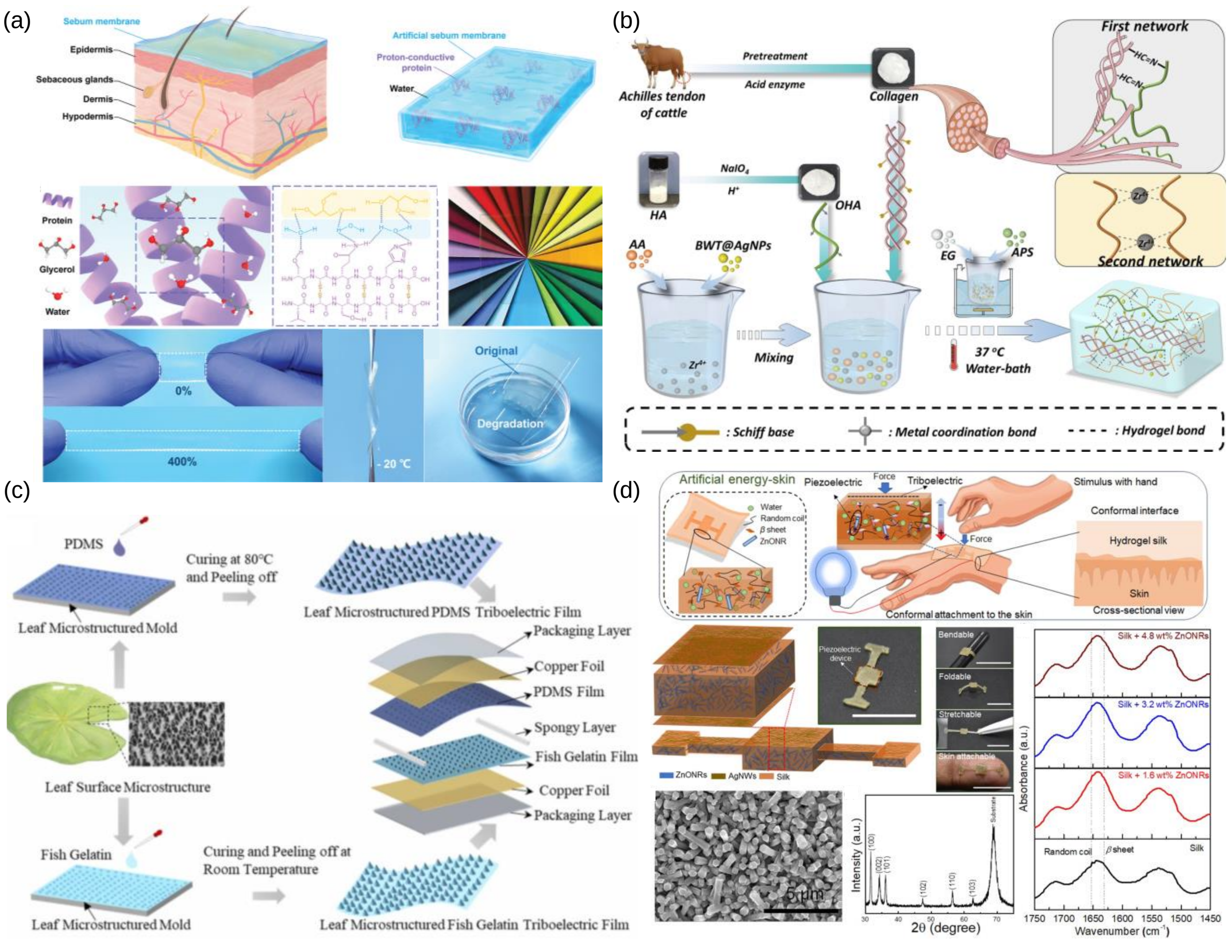

Figure 6. Hydrogel materials are used to construct biomimetic TENGs. (**a**) Protein-based e-skin inspired by sebum membranes. Reprinted with permission from Ref. [79]. Copyright 2023, Wiley. (**b**) Collagen-based multifunctional double-network organohydrogel e-skin. Reprinted with permission from Ref. [60]. Copyright 2023, Elsevier. (**c**) Fish gelatin based TENG. Reprinted with permission from Ref. [78]. Copyright 2023, Elsevier. (**d**) E-skin made of silk protein hydrogel. Reprinted with permission from Ref. [81]. Copyright 2020, Elsevier.

Gogurla et al. introduce an innovative energy-generating skin (EG-skin) made from silk protein hydrogel incorporating zinc oxide nanorods (ZnONRs), aimed at harvesting biomechanical energy (Figure 6d) [81]. The preparation of the silk fibroin solution involves boiling Bombyx mori cocoons to remove sericin protein, followed by dissolving silk fibers in a mixture of $CaCl_2$, glycerol, and formic acid, resulting in a stable hydrogel. ZnONRs, synthesized through a hydrothermal process involving zinc acetate dihydrate and triethylamine, are integrated into this silk hydrogel. These nanorods enhance the piezoelectric properties of the silk, vital for the EG-skin's function. The EG-skin's piezoelectric devices are fabricated by embedding silver nanowires (AgNWs) in the silk-ZnONR membrane, formed by casting the nanocomposite solution onto AgNW electrodes and drying. This process is critical for achieving the desired electrical properties. The final device is encapsulated within two thin silks.

4.2. Fiber Material Bionic

Yang et al. present a self-powered virtual olfactory generation (VOG) system, integrating a bionic fibrous membrane (BFM) with electrostatic field accelerated evaporation (EFAE) capabilities, driven by an ultrafast voltage-elevation TENG (UVE-TENG) (Figure 7a) [82]. The system aims to enhance the immersive experience in virtual and augmented reality by incorporating olfactory sensations. Central to the VOG system is the BFM, a multi-layered structure fabricated using electrospinning technology. It comprises three distinct fiber membranes: PP-SBNF, PAN-CFM, and PVDF-FM. Each layer is characterized by different pore sizes, adhering to Murray's law, with PP-SBNF having macro-sized pores, PAN-CFM micron-sized pores, and PVDF-FM sub-micron-sized pores. This arrangement facilitates rapid absorption and self-driven unidirectional water transmission. The BFM's functionality is further enhanced through surface energy modifications, making the fibers hydrophilic. This modification significantly impacts the liquid transmission and evaporation processes. The BFM's performance is rigorously tested, demonstrating its ability to rapidly spread and evaporate water under ambient conditions.

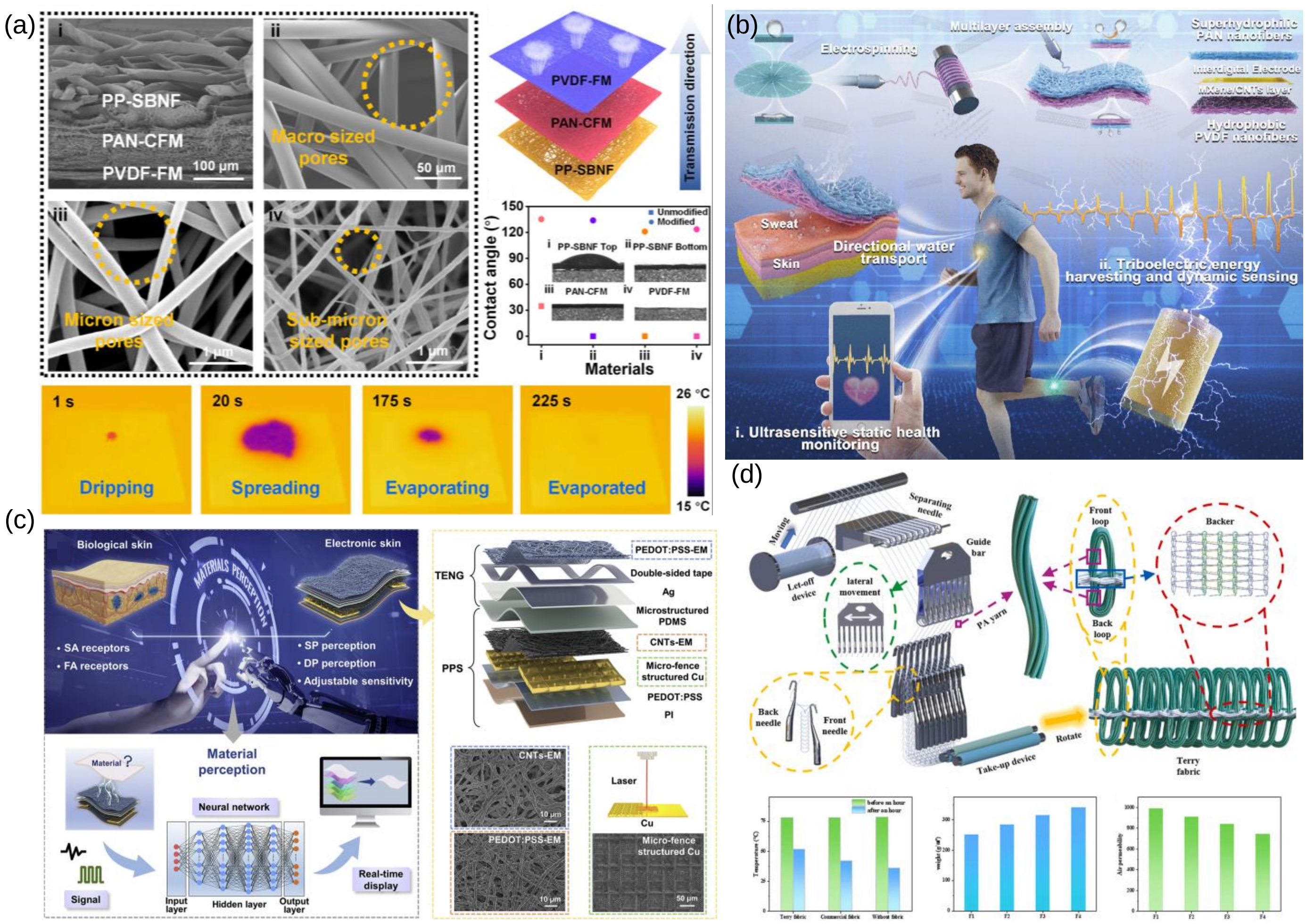

Figure 7. Fiber materials are used to build bionic TENG. (**a**) Biomimetic fiber membrane realizes a virtual smell generation system. Reprinted with permission from Ref. [82]. Copyright 2023, Wiley. (**b**) Bionic full fiber e-skin. Reprinted with permission from Ref. [11]. Copyright 2023, Springer. (**c**) Hybrid e-skin based on eggshell membrane and permeability methods. Reprinted with permission from Ref. [9] Copyright 2022, Cell Press. (**d**) Three-dimensional warp-knitted terry cloth TENG. Reprinted with permission from Ref. [69]. Copyright 2023, Elsevier.

Zhi et al. focuses on the development of a bioinspired directional moisture-wicking e-skin (DMWES), leveraging the principles of heterogeneous fibrous membranes and electrospun conductive layers (Figure 7b) [11]. The DMWES is designed to efficiently manage moisture, particularly sweat, through a unidirectional transfer mechanism, ensuring stable bioelectrical signal acquisition. The DMWES is constructed in a multilayered approach. The base layer consists of hydrophobic carboxylic carbon nanotube (CNT) modified polyvinylidene fluoride (C-PVDF) nanofibers, created through an electrospinning process. This layer serves as the contact interface with the skin, characterized by its low sweat absorption and minimal wetting area. The hydrophobic C-PVDF layer provides a barrier that only allows moisture transfer when a threshold is reached, at which point moisture is drawn into the superhydrophilic PAN layer.

In Figure 7c, Wei et al. introduce a novel hybrid e-skin, combining a piezoresistive pressure sensor (PPS) and a TENG, developed through straightforward preparation methods [57]. The e-skin exhibits the ability to detect both dynamic and static pressure. This e-skin, with its ability to monitor human physiological signals, has significant implications for artificial prostheses, intelligent robots, and HMI. The key feature of this e-skin is the use of a natural eggshell membrane (EM), modified through an infiltration method, to form the PPS and the TENG. This modification imparts the e-skin with material recognition capabilities. The PPS component is designed to detect static and dynamic tactile information. The integration of the e-skin with a high-speed data collector and machine learning enables real-time recognition of 12 different materials through a single touch.

A 3D warp-knitted terry fabric TENG (WKTF-TENG) is introduced by Wang, inspired by animal fur and produced via warp knitting technology (Figure 7d) [69]. This fabric is characterized by its warmth, breathability, gentleness, and comfort, coupled with the capability for mass production. The manufacturing process begins with yarn movement under a let-off device, proceeding through a dividing needle and then forming loop structures with knitting needles and guide bars. Terry fabric's warmth retention is tested with a beaker experiment, showing significantly lower temperature reduction compared to ordinary commercial knitwear and untreated samples. Fabric thickness is controlled by altering the loop height and the air permeability of the fabric decreases as the front loop height increases. The lightweight nature of the fabric is evidenced by its low area weight, even with varying loop heights. Terry fabric demonstrates notable thermal insulation efficacy. In an experimental setup at ambient temperature (27 °C), a beaker coated with terry fabric containing 300 mL hot water exhibited a temperature drop of only 26.6 °C (from 78.1 to 51.5 °C) over one hour, significantly lower than the 36.3 °C decrease (78.1 to 41.8 °C) observed with a similarly treated beaker coated with standard commercial knitwear, and a 42.3 °C reduction (78.4 to 36.1 °C) in an untreated beaker. The thermal resistance of the terry fabric was measured at 0.2678 m^2K/W, with a thermal insulation rate of 75.36%, indicating its superior warmth retention. This enhanced performance is potentially attributable to electrostatic induction effects that maintain the fabric's structural integrity.

4.3. Hydrogel Material Bionics

A bioinspired soft artificial electroreceptor, mimicking the electrosensory system of elasmobranch fishes like sharks, is developed for sensing approaching targets without physical contact (Figure 8a) [4]. The structure of the artificial electroreceptor is composed of a thermally charged elastomeric electret, a conductive organohydrogel layer, and an encapsulating silicone substrate. The organohydrogel, crucial for the functionality of the electroreceptor, is a hybrid polyacrylamide gel containing ethylene glycol (EG) and water as solvents, enhanced by LiCl to improve ionic conductivity. The electret, on the other hand, is a composite material formed by embedding inorganic electret nanoparticles (SiO_2) into a dielectric matrix of PDMS elastomers. This design ensures effective charge trapping by the nanoparticles and stretchability provided by the silicone elastomer. The fabrication process for the organohydrogel involves dissolving acrylamide powder and LiCl in a mixture of deionized water and EG. This mixture is then poured into a mold and allowed to set at room temperature to form the hydrogel. For the electret, SiO_2 nanoparticles are first dispersed in ethyl alcohol, mixed with PDMS precursor, and cured to create a composite film. This film undergoes a thermal charging treatment to enhance its surface charge density.

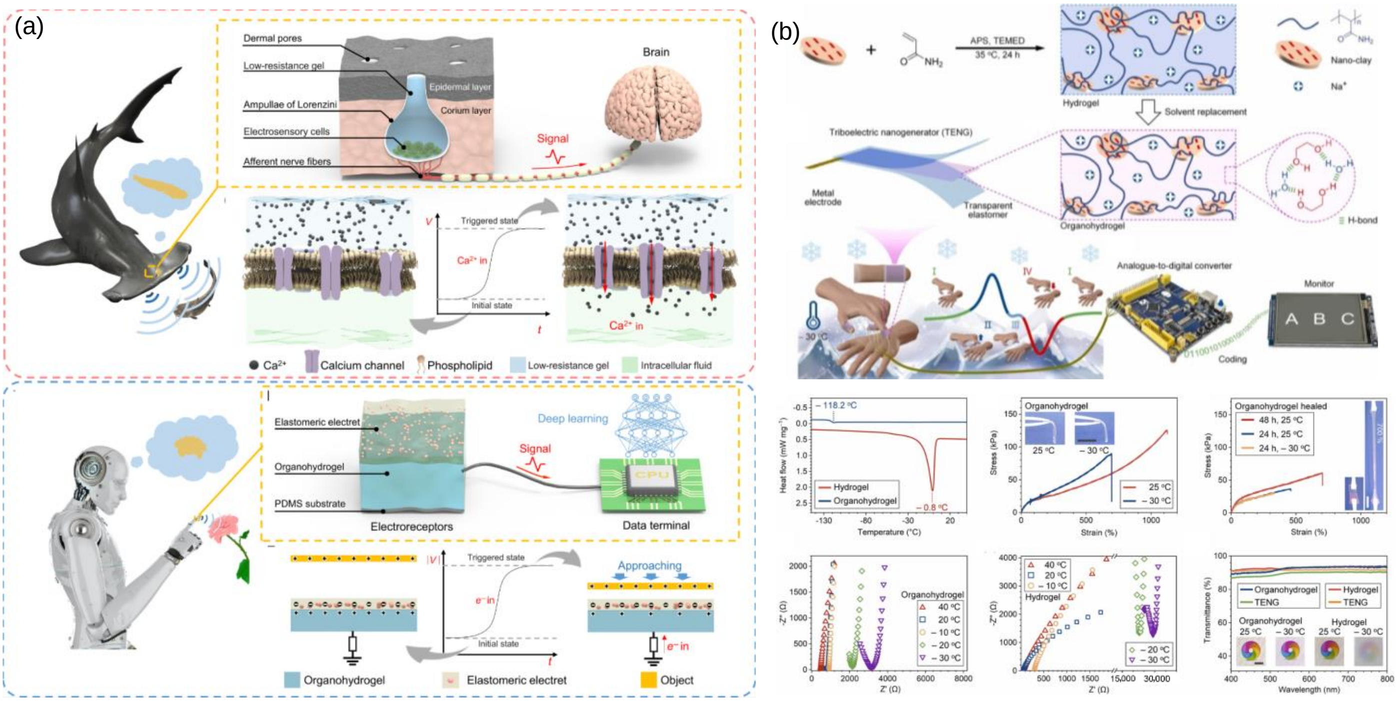

Figure 8. Hydrogel materials are used to construct biomimetic TENGs. (**a**) Bioinspired soft electroreceptors. Reprinted with permission from Ref. [4]. Copyright 2022, American Association for the Advancement of Science. (**b**) Antifreeze organic hydrogel TENG. Reprinted with permission from Ref. [83]. Copyright 2021, Elsevier.

Anti-freezing organohydrogels are developed by Xu et al. to advance flexible human–machine interactive devices, particularly for use in extremely cold environments (Figure 8b) [83]. These organohydrogels comprise polyacrylamide/nano-clays networks absorbing a binary solution of ethylene glycol (EG) and water. The process of preparing these organohydrogels involves synthesizing hydrogels through in-situ polymerization of acrylamide in an aqueous solution of nano-clays, followed by solvent replacement. This method produces a flexible material capable of functioning effectively at subzero temperatures. The resulting organohydrogels maintain their dimensions while acquiring anti-freezing characteristics due to the EG/water solution, which prevents ice crystal formation within the gel structure. These organohydrogels are integrated into TENGs, assembled with elastomers, to create a wearable keyboard. This innovative keyboard is capable of generating voltage signals upon contact with various surfaces. These signals are coded and interpreted into letters and punctuation, then displayed on a monitor, enabling typing at −30 °C.

5. Application of Biomimetic TENGs in E-Skin and HMI

TENGs are at the forefront of bridging biology and technology, particularly revolutionizing the applications in e-skin and HMI. These devices, renowned for their proficiency in converting mechanical energy into electrical signals, predominantly excel in three areas: tactile sensing, motion sensing, and intelligent control. In the domain of tactile sensing, bionic TENGs integrated into e-skin systems demonstrate remarkable capabilities in emulating human skin's sensitivity. They adeptly detect various tactile stimuli, such as pressure and texture, making them indispensable in fields like prosthetics, robotics, and wearable technology. This ability to impart a sense of touch to artificial systems is not only transformative in enhancing the human–machine interface but is also crucial in creating more interactive and responsive systems. In motion sensing, bionic TENGs showcase exceptional accuracy in capturing a range of motions, from subtle gestures to complex bodily dynamics. This precision is particularly vital in HMI, where nuanced motion detection translates into sophisticated interface controls, thereby enriching the interaction with digital systems and virtual environments. Furthermore, the integration of these TENGs in intelligent control systems marks a significant advancement in the realm of autonomous and smart devices. Here, they function as self-powered sensors capable of making informed decisions based on the collected sensory data. This level of autonomy in sensing and decision-making heralds a new era of intuitive and efficient human–machine interfaces, where machines can adaptively respond to human actions and preferences in real-time. Overall, the application of bionic TENGs in e-skin and HMI is a testament to the profound implications of biomimicry in technological advancements. They offer a seamless integration between organic and electronic realms, opening new avenues in the way humans interact with machines, thereby enriching our technological experiences and capabilities.

5.1. Tactile Sensing

Yao et al. developed a bioinspired TENG as a self-powered e-skin sensor, specifically designed for robotic tactile sensing (Figure 9a) [26]. The sensor's design is inspired by the surface morphology of natural plants, particularly the replication of Calathea zebrine leaf's cone-like array microstructures on tribo-layers, which enhances the triboelectric effects. To further increase sensitivity for pressure measurement, PTFE tiny burrs are formed on the microstructured tribo-surface, resulting in a 14-fold increase in sensitivity. This TENG e-skin sensor's tactile sensing capabilities are demonstrated in various applications. First, it is used to measure the handshaking pressure and bending angles of each finger of a bionic hand during handshaking with a human. This application highlights its potential in HMIs, particularly in areas like prosthetics and robotics where the replication of human tactile sensing is crucial. Additionally, the sensor is capable of tactile object recognition. It can measure surface roughness and discern object hardness, which is pivotal for robotic applications where understanding the texture and hardness of objects is necessary for effective manipulation. These capabilities are demonstrated through experiments where the sensor is applied to distinguish the roughness of different grades of sandpaper and the hardness of various polyurethane (PU) foams.

Zhao et al. introduce a fingerprint-inspired e-skin (FE-skin) based on a TENG, designed to replicate human tactile perception for fine texture recognition (Figure 9b) [61]. The FE-skin is capable of detecting changes in contact area caused by dynamic interaction with various surfaces, discerning textures as fine as 6.5 μm. This is achieved through a biomimetic design inspired by human fingerprints, which enhances the sensor's sensitivity to textural variations. A feature of this is its capacity to process complex electrical signals generated during tactile interactions using artificial neural networks (ANNs). This approach allows for the effective identification of different textures by analyzing the nuances in the electrical signals produced when the FE-skin interacts with various surfaces. In tests involving the recognition of disordered (such as different grades of sandpaper) and ordered textures (like Braille characters), the FE-skin's ability to map surface textures to electrical signals and its integration with ANNs for signal processing make it a highly effective system for tactile perception. This technology holds significant potential for applications in precise HMIs, intelligent prostheses, and humanoid robots.

Zhu et al. developed a self-powered bionic antenna (SBA) that emulates the structure and function of insect antennae for robotic tactile sensing (Figure 9c) [71]. This enables the SBA to identify different contact materials, similar to how insect antennae gather environmental information. The SBA comprises a porous conductive sponge (ACES), coated with silver nanowires (AgNW), and functions as the sensor, responding to direct contact with external objects. The metal wire, analogous to an insect's antennal nerve, transmits signals from the ACES to the robot's processing unit. The two-stage actuator, inspired by insect muscle fibers, enables controlled movement of the SBA, enhancing the robot's interactive and exploratory capabilities. In practical applications, the SBA demonstrates effectiveness in obstacle avoidance, instruction acquisition, and environmental recognition for a piezoelectric micro-robot. The SBA's ability to distinguish different materials through touch, coupled with its directional movement control, allows the robot to navigate and respond to its environment intelligently and safely.

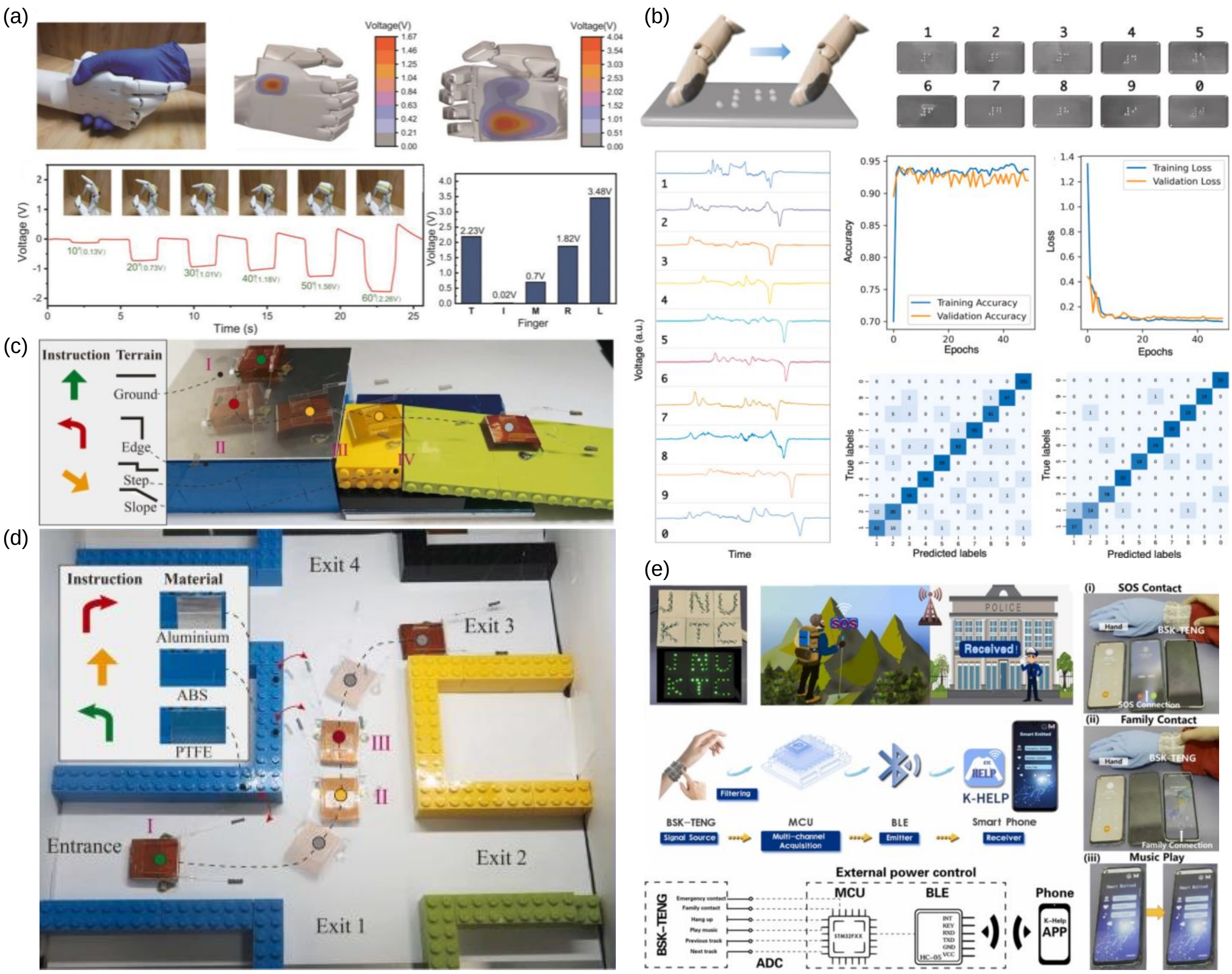

Figure 9. Bioinspired TENG for tactile sensing. (**a**) Calathea zebrine leaf bionic TENG is used for tactile sensing. Reprinted with permission from Ref. [26]. Copyright 2020, Wiley. (**b**) Fingerprint-inspired TENG for tactile sensing. Reprinted with permission from Ref. [61]. Copyright 2021, Elsevier. (**c**,**d**) Bionic antenna TENG is used for tactile sensing in microrobots. Reprinted with permission from Ref. [71]. Copyright 2023, Elsevier. (**e**) Bionic scale weaving for tactile sensing. Reprinted with permission from Ref. [78]. Copyright 2022, Elsevier.

In Figure 9d, a novel wearable fabric termed bionic scales knitting TENG (BSK-TENG) is developed by Niu et al., leveraging biomimetic design and tactile sensing technologies [78]. This fabric, produced using an innovative V-bed flat knitting technology, maintains softness, comfort, and breathability while incorporating intelligence and multifunctionality. A distinctive feature of BSK-TENG is its ability to harvest energy from water droplets and biomechanical sources in outdoor settings, thanks to its unique three-dimensional hierarchical structure. One of the most noteworthy applications highlighted in the study is the utilization of BSK-TENG as a self-powered wearable human-computer interaction sensor within a personal outdoor rescue system. As depicted in Figure 6, this system employs wireless signal transmission to facilitate a range of functionalities. The integration of BSK-TENG in this context demonstrates its potential in transforming mechanical energy into electrical signals for various practical applications, significantly enhancing the scope of wearable electronics in outdoor and emergency scenarios.

5.2. Motion Sensing

In Figure 10a, a bionic-antennae-array (BAA) sensor, inspired by the sensing capabilities of cockroach antennae and based on the TENG principle, is developed for noncontact motion detection [58]. The sensor's structure comprises an array of conductive fibers integrated into a triboelectric dielectric film, facilitating the identification of noncontact motions with high sensitivity. This BAA sensor exhibits a remarkable detection range of up to 180 mm, a fine displacement resolution of 1 mm, and a maximum sensitivity of approximately 5.6 V/mm at a 90° approach angle. Critical performance factors such as the approach angle, motion velocity, and target materials are thoroughly evaluated, elucidating the sensor's robustness in varied conditions. A significant application of this BAA sensor is demonstrated in its integration with intelligent robots and mobile vehicles for motion alarming and obstacle detection functions. This integration highlights the sensor's potential in industrial robotics and HMIs, leveraging its high sensitivity and facile manufacturing process. The BAA sensor's ability to detect noncontact motions and convert these into electrostatic signals for microcontroller units paves the way for diverse applications in fields such as artificial intelligence and the Internet of Things. This development represents a notable advancement in self-powered sensor technology, offering a cost-effective and efficient solution for enhancing the capabilities of autonomous systems and intelligent devices in interacting with and responding to their environment.

Song et al. introduce an application of the PCOBE organohydrogel, focusing on its utilization in motion sensing in Figure 10b [60]. The PCOBE organohydrogel, with its innovative double network structure and incorporation of silver nanoparticles and ethylene glycol, is adept at functioning as a self-powered sensor through a TENG mechanism. The TENG-based self-powered sensing capability of the PCOBE organohydrogel is a standout feature, enabling it to convert mechanical movements into electrical signals without the need for external power sources. This is particularly significant in wearable technology and human motion monitoring, where the flexibility, durability, and self-sufficiency of sensors are crucial. In practical applications, the PCOBE-TENG sensor exhibits excellent performance in detecting various human movements. When attached to different body parts like the wrist, elbow, or knee, the sensor responds to movements such as bending and stretching by generating electrical signals. These signals are reliably consistent in amplitude and frequency, indicating the sensor's accuracy and sensitivity.

Wang et al. developed a plant bionic hybrid self-powered sensor (PBHS) for recognizing motor tics associated with Tourette syndrome (TS), leveraging the capabilities of piezoelectric and TENGs (Figure 10c) [77]. A key feature of the sensor is its biomimetic design, where the PDMS layer mimics the surface structure of Nymphaea tetragona, providing an effective nano-microscale texture for triboelectricity generation. This structure, combined with the piezoelectric properties of the PVDF-TrFE nanofibers, results in a substantial improvement in voltage output, nearly 200% higher than the original PVDF-TrFE nanogenerator. The PBHS's effectiveness in motor tic recognition is further augmented by integrating a deep learning long short-term memory (LSTM) model, part of a recurrent neural network (RNN) system. This model analyzes the sensor's output to identify specific motor tic patterns in TS patients, achieving an 88.1% accuracy rate in signal recognition. Such capability is crucial for medical practitioners to monitor and assess the condition of TS patients remotely and accurately.

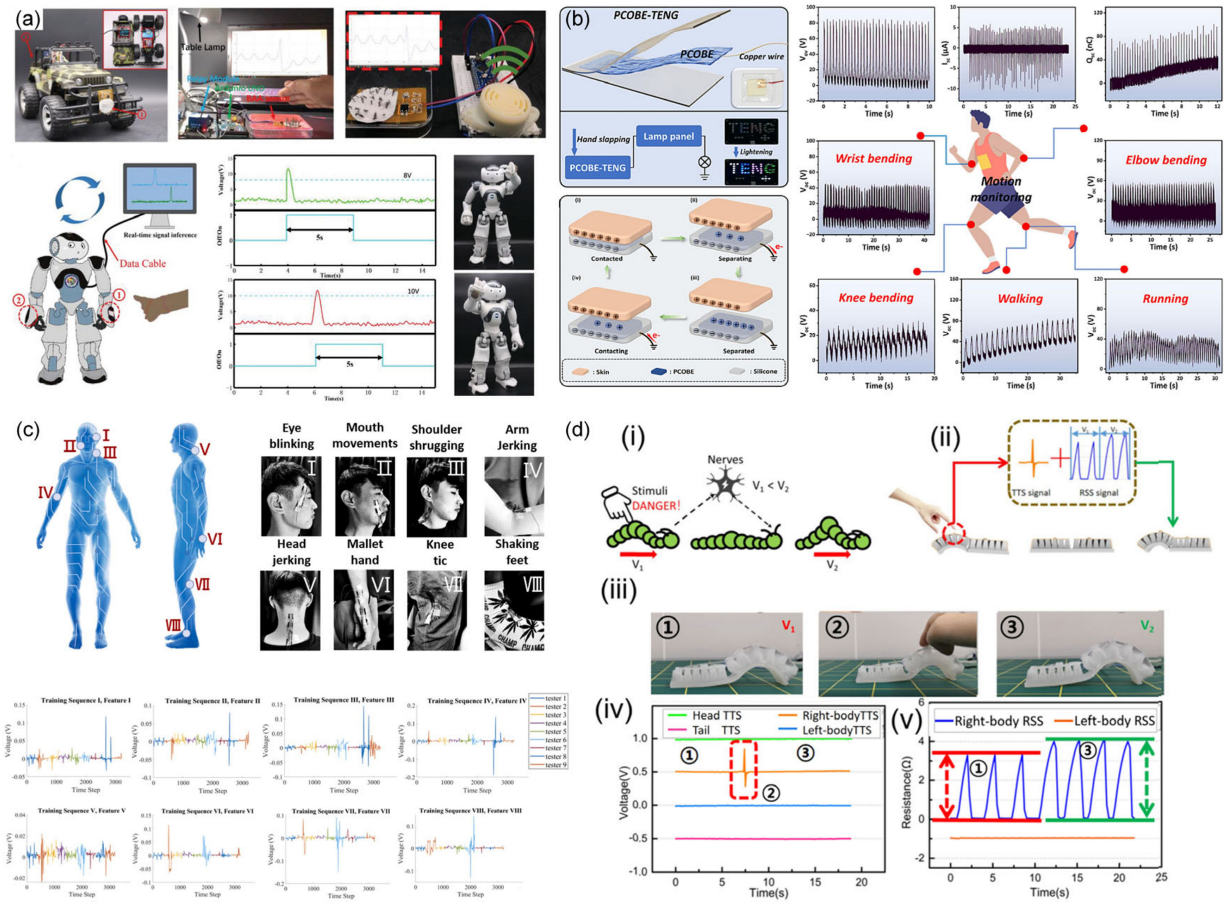

Figure 10. Bioinspired TENG for motion sensing. (**a**) Cockroach tentacle-inspired TENG for non-contact motion recognition. Reprinted with permission from Ref. [58]. Copyright 2022, Wiley. (**b**) Skin bionic TENG for motion monitoring. Reprinted with permission from Ref. [60]. Copyright 2023, Elsevier. (**c**) Biomimetic TENG for hybrid sensing for motion twitch recognition. Reprinted with permission from Ref. [77]. Copyright 2022, Elsevier. (**d**) Bionic soft caterpillar robot. Reprinted with permission from Ref. [84]. Copyright 2021, Elsevier.

A Bioinspired soft caterpillar robot (SCR) is developed by Jin et al. [84], integrating ultra-stretchable bionic sensors into a dual air-chamber pneumatic network structure (Figure 10d). The robot is equipped with two types of sensors: four TENG tactile sensors (TTSs) and two ultra-stretchable resistive strain sensors (RSSs). The TTSs, enhanced with thorny-structured bionic whiskers, enable the SCR to detect tactile stimuli with high sensitivity, responding quickly (0.03 s response time) to external pressures as low as 0.05 kPa. The RSSs, covered as bionic skin and made using functional liquid metal (FLM), are designed to sense and adapt to the robot's body deformations. With a sensitivity of 2.94 and an ability to withstand up to 180% strain, these RSSs efficiently monitor and adjust the robot's crawling and bending movements. The SCR demonstrates advanced biological perception abilities, essential for mimicking bionic actions and responses in unknown environments. This includes escaping from unexpected threats and adaptively crawling through unfamiliar tunnel-like spaces. The TTSs, attached to the robot's head, tail, and body, are crucial for environmental interaction, enabling the SCR to respond to and navigate through complex surroundings. Meanwhile, the RSSs provide the robot with a heightened awareness of its own body's position and movements, allowing for precise and adaptable locomotion.

5.3. Intelligent Control

Zhou et al. presents a groundbreaking development in human–machine interface (HMI) technology, particularly for assisting people with disabilities in communication (Figure 11a) [59]. Inspired by frogs' croaking behavior, the researchers developed a bionic TENG-based ultra-sensitive self-powered electromechanical (BTUSE) sensor. This sensor is capable of converting the micromotion of muscles, specifically the masseter muscle, into electrical signals for HMI control. A novel aspect of this research is the integration of machine learning algorithms and Morse code to achieve a reliable, safe, and accurate (96.3%) communication aid for disabled users. The BTUSE sensor's advanced capabilities enable the translation of subtle muscle movements into distinct Morse code signals, which are then interpreted by the system to facilitate communication. The system's intelligent control is further exemplified in an authentication system, where the sensor's signals, representing muscle movements, are analyzed and recognized through software platforms using support vector machine (SVM) algorithms and principal component analysis (PCA). This allows for secure and personalized access to the communication system, enhancing user privacy and security. In practical applications, the BTUSE sensor's exceptional sensitivity and range make it particularly useful for disabled individuals who have limited communication abilities. For instance, the hands-free typing communication system developed in this study empowers users to communicate complex messages, including letters and sentences, by simple muscle movements (Figure 11b).

Zhang et al. present an innovative bionic TENG (bTENG) as a self-powered motion sensor for wake-up circuits in smart microsystems (Figure 11c) [76]. The bTENG, designed to mimic plant structures with leaf-shaped tentacles, significantly enhances pressure-triggering sensitivity and reduces power consumption. It efficiently captures slight mechanical disturbances, overcoming the limitations of conventional self-powered motion sensors that only respond to considerable pressure. The bTENG features leaf-shaped tentacle structures, which amplify its electrical output by four times compared to a flat base design. The generated voltages from these disturbances are sufficient to trigger the wake-up system, highlighting its sensitivity and efficiency. This integration of the bTENG into the wake-up circuit demonstrates a substantial advancement in energy conservation for unmanned electronic networks. Additionally, the system includes an intrusion detection feature capable of distinguishing human motion and assessing the scene based on audio signals recorded post-activation. This intelligent aspect adds a layer of security and adaptability to the system.

Gong et al. present a novel artificial bionic skin, designed for advanced HMI applications, which integrates exceptional environmental stability, reconfigurability, and multifunctional sensory capabilities (Figure 11d) [62]. The skin's multifunctional sensory properties, mirroring those of natural skin, enable it to detect and respond to various stimuli such as strain, stress, temperature, solvent, and bioelectricity. The study demonstrates the application of this artificial skin in creating an interactive HMI system. The skin, when integrated with electronic devices, can adhere comfortably to the human body, enabling wireless motion capture and sensory feedback through Bluetooth, Wi-Fi, and the Internet. The system's versatility is showcased through its ability to control a high-degree-of-freedom robot in real-time, mimicking complex human motions. This capability has significant implications for applications in extreme environment operations, fire rescue, and exoskeleton control, offering a safer alternative to direct human involvement in hazardous situations.

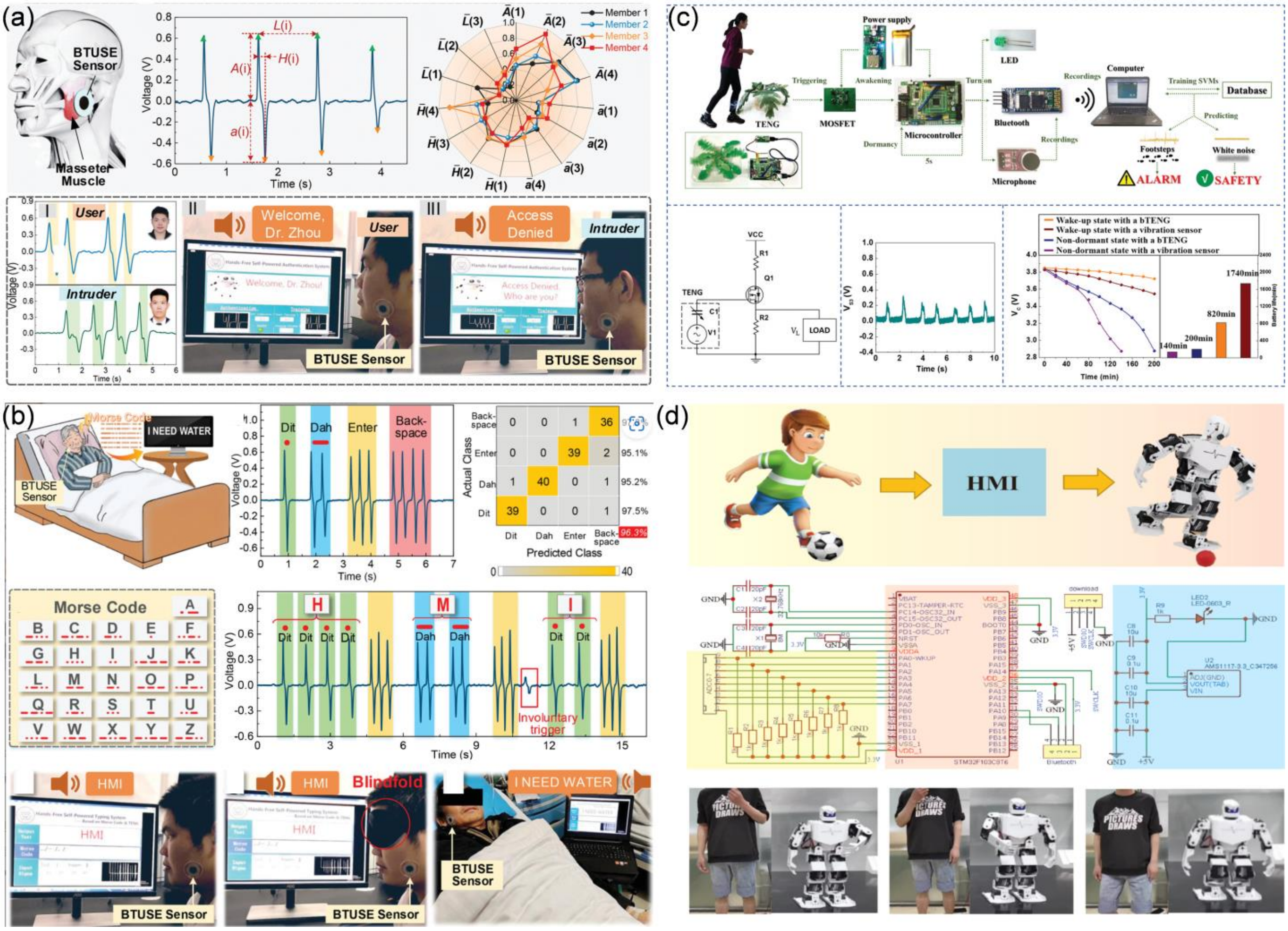

Figure 11. Bioinspired TENG for intelligent control. (**a**,**b**) Bionic TENG for HMI applications. Reprinted with permission from Ref. [59]. Copyright 2021, Wiley. (**c**) The leaf-like tentacle plant structure bionic TENG is used for system awakening. Reprinted with permission from Ref. [76]. Copyright 2020, Wiley. (**d**) Artificial bionic skin for multi-sensory HMI. Reprinted with permission from Ref. [62]. Copyright 2022, American Chemical Society.

6. Conclusions and Perspectives

In this review, we have meticulously explored the recent advancements in bioinspired TENGs, focusing on their transformative impact on e-skins and HMI. We started with a foundational understanding of TENGs, discussing their diverse operational modes and setting the stage for appreciating their versatility in energy harvesting and sensory applications. Our examination of structural biomimicry, inspired by the intricacies of plant and animal forms, highlighted how nature's designs are ingeniously integrated into TENGs to enhance their efficiency and adaptability. We also delved into material biomimicry, emphasizing the role of proteins, fibers, and hydrogels in advancing TENGs' flexibility, durability, and biocompatibility. Our analysis clearly shows that these developments hold significant promise for the future of e-skins, with TENGs poised to revolutionize wearable technologies and robotic systems through advanced capabilities in tactile and motion sensing, as well as in intelligent control.

Looking ahead, we see several exciting avenues for the advancement of bioinspired TENGs, primarily focusing on performance enhancement, large-scale fabrication, and system integration. We believe that enhancing performance is crucial and future research should aim at optimizing energy conversion efficiency and output power. This may involve new material discoveries and advancements in micro-nanostructuring for higher triboelectric charges and more effective energy conversion. Another critical area is the large-scale fabrication of TENGs. As the demand for wearable and interactive technologies grows, we recognize the need for scalable and cost-effective production methods. This will require innovative manufacturing techniques that can maintain the quality and performance of TENGs while reducing production costs. In addition, optimizing the bionic structures within TENGs represents a key challenge and opportunity. Future research should focus on advancing the biomimetic aspects of TENGs, enhancing their mimicry of natural systems for improved adaptability and efficiency in diverse environments. This involves interdisciplinary efforts to refine the synergy between biological inspiration and technological implementation, aiming to unlock new potentials in tactile sensing and HMIs. Finally, system integration presents a vital challenge and opportunity. We anticipate that future research will focus on creating TENGs that are not only efficient and scalable but also versatile for integration with various electronic systems. This will enhance the overall utility and functionality of e-skins and HMI devices, making these bioinspired TENGs more accessible and applicable in everyday technology. Addressing compatibility with existing technologies, user comfort, and long-term durability will be key to transitioning these bioinspired TENGs from laboratory innovations to mainstream applications.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sun, Z.; Zhu, M.; Shan, X.; Lee, C. Augmented tactile-perception and haptic-feedback rings as human-machine interfaces aiming for immersive interactions. *Nat. Commun.* **2022**, *13*, 5224. [CrossRef] [PubMed]
2. Dong, B.; Zhang, Z.; Shi, Q.; Wei, J.; Ma, Y.; Xiao, Z.; Lee, C. Biometrics-protected optical communication enabled by deep learning–enhanced triboelectric/photonic synergistic interface. *Sci. Adv.* **2022**, *8*, eabl9874. [CrossRef]
3. Li, J.; Carlos, C.; Zhou, H.; Sui, J.; Wang, Y.; Silva-Pedraza, Z.; Yang, F.; Dong, Y.; Zhang, Z.; Hacker, T.A.; et al. Stretchable piezoelectric biocrystal thin films. *Nat. Commun.* **2023**, *14*, 6562. [CrossRef]
4. Guo, Z.H.; Wang, H.L.; Shao, J.; Shao, Y.; Jia, L.; Li, L.; Pu, X.; Wang, Z.L. Bioinspired soft electroreceptors for artificial precontact somatosensation. *Sci. Adv.* **2022**, *8*, eabo5201. [CrossRef] [PubMed]
5. Wong, T.H.; Liu, Y.; Li, J.; Yao, K.; Liu, S.; Yiu, C.K.; Huang, X.; Wu, M.; Park, W.; Zhou, J.; et al. Triboelectric Nanogenerator Tattoos Enabled by Epidermal Electronic Technologies. *Adv. Funct. Mater.* **2022**, *32*, 2111269. [CrossRef]
6. Shi, Q.; Sun, Z.; Le, X.; Xie, J.; Lee, C. Soft Robotic Perception System with Ultrasonic Auto-Positioning and Multimodal Sensory Intelligence. *ACS Nano* **2023**, *17*, 4985–4998. [CrossRef]
7. Sun, Z.; Zhu, M.; Lee, C. Progress in the Triboelectric Human–Machine Interfaces (HMIs)-Moving from Smart Gloves to AI/Haptic Enabled HMI in the 5G/IoT Era. *Nanoenergy Adv.* **2021**, *1*, 81–120. [CrossRef]
8. Peng, X.; Dong, K.; Zhang, Y.; Wang, L.; Wei, C.; Lv, T.; Wang, Z.L.; Wu, Z. Sweat-Permeable, Biodegradable, Transparent and Self-powered Chitosan-Based Electronic Skin with Ultrathin Elastic Gold Nanofibers. *Adv. Funct. Mater.* **2022**, *32*, 2112241. [CrossRef]
9. Wei, X.; Li, H.; Yue, W.; Gao, S.; Chen, Z.; Li, Y.; Shen, G. A high-accuracy, real-time, intelligent material perception system with a machine-learning-motivated pressure-sensitive electronic skin. *Matter* **2022**, *5*, 1481–1501. [CrossRef]
10. Li, X.; Zhu, P.; Zhang, S.; Wang, X.; Luo, X.; Leng, Z.; Zhou, H.; Pan, Z.; Mao, Y. A Self-Supporting, Conductor-Exposing, Stretchable, Ultrathin, and Recyclable Kirigami-Structured Liquid Metal Paper for Multifunctional E-Skin. *ACS Nano* **2022**, *16*, 5909–5919. [CrossRef]
11. Zhi, C.; Shi, S.; Zhang, S.; Si, Y.; Yang, J.; Meng, S.; Fei, B.; Hu, J. Bioinspired All-Fibrous Directional Moisture-Wicking Electronic Skins for Biomechanical Energy Harvesting and All-Range Health Sensing. *Nano-Micro Lett.* **2023**, *15*, 60. [CrossRef]
12. Tao, K.; Yu, J.; Zhang, J.; Bao, A.; Hu, H.; Ye, T.; Ding, Q.; Wang, Y.; Lin, H.; Wu, J.; et al. Deep-Learning Enabled Active Biomimetic Multifunctional Hydrogel Electronic Skin. *ACS Nano* **2023**, *17*, 16160–16173. [CrossRef]
13. Shi, Q.; Zhang, Z.; He, T.; Sun, Z.; Wang, B.; Feng, Y.; Shan, X.; Salam, B.; Lee, C. Deep learning enabled smart mats as a scalable floor monitoring system. *Nat. Commun.* **2020**, *11*, 4609. [CrossRef] [PubMed]
14. Wang, Z.; Li, N.; Zhang, Z.; Cui, X.; Zhang, H. Hydrogel-Based Energy Harvesters and Self-Powered Sensors for Wearable Applications. *Nanoenergy Adv.* **2023**, *3*, 315–342. [CrossRef]
15. Qi, M.; Yang, R.; Wang, Z.; Liu, Y.; Zhang, Q.; He, B.; Li, K.; Yang, Q.; Wei, L.; Pan, C.; et al. Bioinspired Self-healing Soft Electronics. *Adv. Funct. Mater.* **2023**, *33*, 2214479. [CrossRef]

16. Lin, X.; Bing, Y.; Li, F.; Mei, H.; Liu, S.; Fei, T.; Zhao, H.; Zhang, T. An All-Nanofiber-Based, Breathable, Ultralight Electronic Skin for Monitoring Physiological Signals. *Adv. Mater. Technol.* **2022**, *7*, 2101312. [CrossRef]
17. Zeng, X.; Liu, Y.; Liu, F.; Wang, W.; Liu, X.; Wei, X.; Hu, Y. A bioinspired three-dimensional integrated e-skin for multiple mechanical stimuli recognition. *Nano Energy* **2022**, *92*, 106777. [CrossRef]
18. Lu, D.; Liu, T.; Meng, X.; Luo, B.; Yuan, J.; Liu, Y.; Zhang, S.; Cai, C.; Gao, C.; Wang, J.; et al. Wearable Triboelectric Visual Sensors for Tactile Perception. *Adv. Mater.* **2023**, *35*, 2209117. [CrossRef]
19. Zhang, C.; Li, Z.; Li, H.; Yang, Q.; Wang, H.; Shan, C.; Zhang, J.; Hou, X.; Chen, F. Femtosecond Laser-Induced Supermetalphobicity for Design and Fabrication of Flexible Tactile Electronic Skin Sensor. *ACS Appl. Mater. Interfaces* **2022**, *14*, 38328–38338. [CrossRef] [PubMed]
20. Jia, C.; Xia, Y.; Zhu, Y.; Wu, M.; Zhu, S.; Wang, X. High-Brightness, High-Resolution, and Flexible Triboelectrification-Induced Electroluminescence Skin for Real-Time Imaging and Human–Machine Information Interaction. *Adv. Funct. Mater.* **2022**, *32*, 2201292. [CrossRef]
21. Xie, Y.; Ma, Q.; Yue, B.; Chen, X.; Jin, Y.; Qi, H.; Hu, Y.; Yu, W.; Dong, X.; Jiang, H. Triboelectric nanogenerator based on flexible Janus nanofiber membrane with simultaneous high charge generation and charge capturing abilities. *Chem. Eng. J.* **2023**, *452*, 139393. [CrossRef]
22. Kim, Y.; Suh, J.M.; Shin, J.; Liu, Y.; Yeon, H.; Qiao, K.; Kum, H.S.; Kim, C.; Lee, H.E.; Choi, C.; et al. Chip-less wireless electronic skins by remote epitaxial freestanding compound semiconductors. *Science* **2022**, *377*, 859–864. [CrossRef] [PubMed]
23. Liu, F.; Deswal, S.; Christou, A.; Sandamirskaya, Y.; Kaboli, M.; Dahiya, R. Neuro-inspired electronic skin for robots. *Sci. Robot.* **2022**, *7*, eabl7344. [CrossRef] [PubMed]
24. Song, Z.; Yin, J.; Wang, Z.; Lu, C.; Yang, Z.; Zhao, Z.; Lin, Z.; Wang, J.; Wu, C.; Cheng, J.; et al. A flexible triboelectric tactile sensor for simultaneous material and texture recognition. *Nano Energy* **2022**, *93*, 106798. [CrossRef]
25. Li, G.; Zhang, M.; Liu, S.; Yuan, M.; Wu, J.; Yu, M.; Teng, L.; Xu, Z.; Guo, J.; Li, G.; et al. Three-dimensional flexible electronics using solidified liquid metal with regulated plasticity. *Nat. Electron.* **2023**, *6*, 154–163. [CrossRef]
26. Yao, G.; Xu, L.; Cheng, X.; Li, Y.; Huang, X.; Guo, W.; Liu, S.; Wang, Z.L.; Wu, H. Bioinspired Triboelectric Nanogenerators as Self-Powered Electronic Skin for Robotic Tactile Sensing. *Adv. Funct. Mater.* **2020**, *30*, 1907312. [CrossRef]
27. Li, W.; Lu, L.; Kottapalli, A.G.P.; Pei, Y. Bioinspired sweat-resistant wearable triboelectric nanogenerator for movement monitoring during exercise. *Nano Energy* **2022**, *95*, 107018. [CrossRef]
28. Dong, J.; Zhu, L.; Guo, P.; Xu, C.; Zhao, X.; Yang, S.; He, X.; Zhou, G.; Ma, G.; Guo, H.; et al. A bio-inspired total current nanogenerator. *Energy Environ. Sci.* **2023**, *16*, 1071–1081. [CrossRef]
29. Xue, J.; Zou, Y.; Deng, Y.; Li, Z. Bioinspired sensor system for health care and human-machine interaction. *EcoMat* **2022**, *4*, e12209. [CrossRef]
30. Yeh, C.; Kao, F.-C.; Wei, P.-H.; Pal, A.; Kaswan, K.; Huang, Y.-T.; Parashar, P.; Yeh, H.-Y.; Wang, T.-W.; Tiwari, N.; et al. Bioinspired shark skin-based liquid metal triboelectric nanogenerator for self-powered gait analysis and long-term rehabilitation monitoring. *Nano Energy* **2022**, *104*, 107852. [CrossRef]
31. Dong, B.; Yang, Y.; Shi, Q.; Xu, S.; Sun, Z.; Zhu, S.; Zhang, Z.; Kwong, D.-L.; Zhou, G.; Ang, K.-W.; et al. Wearable Triboelectric–Human–Machine Interface (THMI) Using Robust Nanophotonic Readout. *ACS Nano* **2020**, *14*, 8915–8930. [CrossRef] [PubMed]
32. Qiu, X.; Liu, J.; Zhou, B.; Zhang, X. Bioinspired Bimodal Mechanosensors with Real-Time, Visualized Information Display for Intelligent Control. *Adv. Funct. Mater.* **2023**, *33*, 2300321. [CrossRef]
33. Shi, Q.; Lee, C. Self-Powered Bio-Inspired Spider-Net-Coding Interface Using Single-Electrode Triboelectric Nanogenerator. *Adv. Sci.* **2019**, *6*, 1900617. [CrossRef]
34. Hajra, S.; Panda, S.; Khanberh, H.; Vivekananthan, V.; Chamanehpour, E.; Mishra, Y.K.; Kim, H.J. Revolutionizing self-powered robotic systems with triboelectric nanogenerators. *Nano Energy* **2023**, *115*, 108729. [CrossRef]
35. Ye, G.; Wan, Y.; Wu, J.; Zhuang, W.; Zhou, Z.; Jin, T.; Zi, J.; Zhang, D.; Geng, X.; Yang, P. Multifunctional device integrating dual-temperature regulator for outdoor personal thermal comfort and triboelectric nanogenerator for self-powered human-machine interaction. *Nano Energy* **2022**, *97*, 107148. [CrossRef]
36. Wang, M.; Dong, L.; Wu, J.; Shi, J.; Gao, Q.; Zhu, C.; Morikawa, H. Leaf-meridian bio-inspired nanofibrous electronics with uniform distributed microgrid and 3D multi-level structure for wearable applications. *NPJ Flex. Electron.* **2022**, *6*, 34. [CrossRef]
37. Yao, S.; Zhao, X.; Wang, X.; Huang, T.; Ding, Y.; Zhang, J.; Zhang, Z.; Wang, Z.L.; Li, L. Bioinspired Electron Polarization of Nanozymes with a Human Self-Generated Electric Field for Cancer Catalytic Therapy. *Adv. Mater.* **2022**, *34*, 2109568. [CrossRef] [PubMed]
38. Li, X.; Mu, J.; He, J.; Fan, X.; Zhang, Q.; Hou, X.; Geng, W.; Zhang, W.; Chou, X. Bioinspired Helical Triboelectric Nanogenerators for Energy Conversion of Motion. *Adv. Mater. Technol.* **2020**, *5*, 1900917. [CrossRef]
39. Hu, Y.; Teng, Y.; Sun, Y.; Liu, P.; Fu, L.; Yang, L.; Kong, X.-Y.; Zhao, Q.; Jiang, L.; Wen, L. Bioinspired poly (ionic liquid) membrane for efficient salinity gradient energy harvesting: Electrostatic crosslinking induced hierarchical nanoporous network. *Nano Energy* **2022**, *97*, 107170. [CrossRef]
40. Pandey, A.; Yang, T.-S.; Yang, T.-I.; Belem, W.F.; Teng, N.-C.; Chen, I.W.; Huang, C.-S.; Kareiva, A.; Yang, J.-C. An Insight into Nano Silver Fluoride-Coated Silk Fibroin Bioinspired Membrane Properties for Guided Tissue Regeneration. *Polymers* **2021**, *13*, 2659. [CrossRef]

41. Chen, Z.; Yu, R.; Yu, X.; Li, E.; Wang, C.; Liu, Y.; Guo, T.; Chen, H. Bioinspired Artificial Motion Sensory System for Rotation Recognition and Rapid Self-Protection. *ACS Nano* **2022**, *16*, 19155–19164. [CrossRef] [PubMed]
42. Zhang, C.; Li, S.; He, Y.; Chen, C.; Jiang, S.; Yang, X.; Wang, X.; Pan, L.; Wan, Q. Oxide Synaptic Transistors Coupled With Triboelectric Nanogenerators for Bio-Inspired Tactile Sensing Application. *IEEE Electron. Device Lett.* **2020**, *41*, 617–620. [CrossRef]
43. Zhang, J.-H.; Li, Y.; Du, J.; Hao, X.; Wang, Q. Bio-inspired hydrophobic/cancellous/hydrophilic Trimurti PVDF mat-based wearable triboelectric nanogenerator designed by self-assembly of electro-pore-creating. *Nano Energy* **2019**, *61*, 486–495. [CrossRef]
44. Chung, K.Y.; Xu, B.; Li, Z.; Liu, Y.; Han, J. Bioinspired ultra-stretchable dual-carbon conductive functional polymer fiber materials for health monitoring, energy harvesting and self-powered sensing. *Chem. Eng. J.* **2023**, *454*, 140384. [CrossRef]
45. Feng, T.; Ling, D.; Li, C.; Zheng, W.; Zhang, S.; Li, C.; Emel'yanov, A.; Pozdnyakov, A.S.; Lu, L.; Mao, Y. Stretchable on-skin touchless screen sensor enabled by ionic hydrogel. *Nano Res.* **2023**, 1–9. [CrossRef]
46. Xu, J.; Sun, X.; Sun, B.; Zhu, H.; Fan, X.; Guo, Q.; Li, Y.; Zhu, Z.; Qian, K. Stretchable, Adhesive, and Bioinspired Visual Electronic Skin with Strain/Temperature/Pressure Multimodal Non-Interference Sensing. *ACS Appl. Mater. Interfaces* **2023**, *15*, 33774–33783. [CrossRef]
47. Yue, O.; Wang, X.; Liu, X.; Hou, M.; Zheng, M.; Wang, Y.; Cui, B. Spider-Web and Ant-Tentacle Doubly Bio-Inspired Multifunctional Self-Powered Electronic Skin with Hierarchical Nanostructure. *Adv. Sci.* **2021**, *8*, 2004377. [CrossRef]
48. Panda, S.; Hajra, S.; Rajaitha, P.M.; Kim, H.J. Stimuli-responsive polymer-based bioinspired soft robots. *Micro Nano Syst. Lett.* **2023**, *11*, 2. [CrossRef]
49. Yu, J.; Wang, Y.; Qin, S.; Gao, G.; Xu, C.; Lin Wang, Z.; Sun, Q. Bioinspired interactive neuromorphic devices. *Mater. Today* **2022**, *60*, 158–182. [CrossRef]
50. Li, J.; Yuan, Z.; Han, X.; Wang, C.; Huo, Z.; Lu, Q.; Xiong, M.; Ma, X.; Gao, W.; Pan, C. Biologically Inspired Stretchable, Multifunctional, and 3D Electronic Skin by Strain Visualization and Triboelectric Pressure Sensing. *Small Sci.* **2022**, *2*, 2100083. [CrossRef]
51. Li, H.; Lv, S.; Fang, Y. Bio-inspired micro/nanostructures for flexible and stretchable electronics. *Nano Res.* **2020**, *13*, 1244–1252. [CrossRef]
52. Yao, X.; Zou, S.; Fan, S.; Niu, Q.; Zhang, Y. Bioinspired silk fibroin materials: From silk building blocks extraction and reconstruction to advanced biomedical applications. *Mater. Today Bio* **2022**, *16*, 100381. [CrossRef]
53. Bai, L.; Jin, Y.; Shang, X.; Shi, L.; Jin, H.; Zhou, R.; Lai, S. Bio-inspired visual multi-sensing interactive ionic skin with asymmetrical adhesive, antibacterial and self-powered functions. *Chem. Eng. J.* **2022**, *438*, 135596. [CrossRef]
54. Gong, S.; Ding, Q.; Wu, J.; Li, W.-B.; Guo, X.-Y.; Zhang, W.-M.; Shao, L. Bioinspired Multifunctional Mechanoreception of Soft–Rigid Hybrid Actuator Fingers. *Adv. Intell. Syst.* **2022**, *4*, 2100242. [CrossRef]
55. Li, W.; Pei, Y.; Zhang, C.; Kottapalli, A.G.P. Bioinspired designs and biomimetic applications of triboelectric nanogenerators. *Nano Energy* **2021**, *84*, 105865. [CrossRef]
56. Mayer, M.; Xiao, X.; Yin, J.; Chen, G.; Xu, J.; Chen, J. Advances in Bioinspired Triboelectric Nanogenerators. *Adv. Electron. Mater.* **2022**, *8*, 2200782. [CrossRef]
57. Liu, Y.; Chen, B.; Li, W.; Zu, L.; Tang, W.; Wang, Z.L. Bioinspired Triboelectric Soft Robot Driven by Mechanical Energy. *Adv. Funct. Mater.* **2021**, *31*, 2104770. [CrossRef]
58. Wang, F.; Ren, Z.; Nie, J.; Tian, J.; Ding, Y.; Chen, X. Self-Powered Sensor Based on Bionic Antennae Arrays and Triboelectric Nanogenerator for Identifying Noncontact Motions. *Adv. Mater. Technol.* **2020**, *5*, 1900789. [CrossRef]
59. Zhou, H.; Li, D.; He, X.; Hui, X.; Guo, H.; Hu, C.; Mu, X.; Wang, Z.L. Bionic Ultra-Sensitive Self-Powered Electromechanical Sensor for Muscle-Triggered Communication Application. *Adv. Sci.* **2021**, *8*, 2101020. [CrossRef]
60. Song, B.; Fan, X.; Shen, J.; Gu, H. Ultra-stable and self-healing coordinated collagen-based multifunctional double-network organohydrogel e-skin for multimodal sensing monitoring of strain-resistance, bioelectrode, and self-powered triboelectric nanogenerator. *Chem. Eng. J.* **2023**, *474*, 145780. [CrossRef]
61. Zhao, X.; Zhang, Z.; Xu, L.; Gao, F.; Zhao, B.; Ouyang, T.; Kang, Z.; Liao, Q.; Zhang, Y. Fingerprint-inspired electronic skin based on triboelectric nanogenerator for fine texture recognition. *Nano Energy* **2021**, *85*, 106001. [CrossRef]
62. Gong, Y.; Zhang, Y.-Z.; Fang, S.; Sun, Y.; Niu, J.; Lai, W.-Y. Wireless Human–Machine Interface Based on Artificial Bionic Skin with Damage Reconfiguration and Multisensing Capabilities. *ACS Appl. Mater. Interfaces* **2022**, *14*, 47300–47309. [CrossRef]
63. Cao, X.; Xiong, Y.; Sun, J.; Xie, X.; Sun, Q.; Wang, Z.L. Multidiscipline Applications of Triboelectric Nanogenerators for the Intelligent Era of Internet of Things. *Nano Micro Lett.* **2022**, *15*, 14. [CrossRef]
64. Shi, B.; Wang, Q.; Su, H.; Li, J.; Xie, B.; Wang, P.; Qiu, J.; Wu, C.; Zhang, Y.; Zhou, X.; et al. Progress in recent research on the design and use of triboelectric nanogenerators for harvesting wind energy. *Nano Energy* **2023**, *116*, 108789. [CrossRef]
65. Zhang, Z.; Qi, Z.; Sun, X.; Xu, J. A triboelectric nanogenerator based on bionic design for harvesting energy from low-frequency vibration. *Int. J. Non-Linear Mech.* **2023**, *157*, 104540. [CrossRef]
66. Wang, Z.; Cui, J.; Luan, M.; Hao, C.; Zheng, Y.; Xue, C. Robotic pressure sensing sensor based on triboelectric nanogenerator. In Proceedings of the 2022 IEEE International Conference on Cyborg and Bionic Systems (CBS), Wuhan, China, 24–26 March 2023; pp. 336–340.
67. Wang, X.; Liu, J.; Wang, S.; Zheng, J.; Guan, T.; Liu, X.; Wang, T.; Chen, T.; Wang, H.; Xie, G.; et al. A Self-powered Triboelectric Coral-Like Sensor Integrated Buoy for Irregular and Ultra-Low Frequency Ocean Wave Monitoring. *Adv. Mater. Technol.* **2022**, *7*, 2101098. [CrossRef]

68. Ma, G.; Li, B.; Niu, S.; Zhang, J.; Wang, D.; Wang, Z.; Zhou, L.; Liu, Q.; Liu, L.; Wang, J.; et al. A bioinspired triboelectric nanogenerator for all state energy harvester and self-powered rotating monitor. *Nano Energy* **2022**, *91*, 106637. [CrossRef]
69. Wang, T.; Shen, Y.; Chen, L.; Wang, K.; Niu, L.; Liu, G.; He, H.; Cong, H.; Jiang, G.; Zhang, Q.; et al. Large-scale production of the 3D warp knitted terry fabric triboelectric nanogenerators for motion monitoring and energy harvesting. *Nano Energy* **2023**, *109*, 108309. [CrossRef]
70. Wang, Z.; Wan, D.; Cui, X.; Khan, S.A.; Zhuo, K.; Zhang, H. Wearable Electronics Powered by Triboelectrification between Hair and Cloth for Monitoring Body Motions. *Energy Technol.* **2022**, *10*, 2200195. [CrossRef]
71. Zhu, D.; Lu, J.; Zheng, M.; Wang, D.; Wang, J.; Liu, Y.; Wang, X.; Zhang, M. Self-powered bionic antenna based on triboelectric nanogenerator for micro-robotic tactile sensing. *Nano Energy* **2023**, *114*, 108644. [CrossRef]
72. Yao, Y.; Wang, K.; Gao, X.; Zhou, Z.; Liu, Y.; Zhang, J.; Lu, X. Planar Acceleration Sensor for UAV in Cruise State Based on Single-Electrode Triboelectric Nanogenerator. *IEEE Sens. J.* **2023**, *23*, 3041–3049. [CrossRef]
73. Wang, J.; Ma, L.; He, J.; Yao, Y.; Zhu, X.; Peng, L.; Yang, J.; Li, K.; Qu, M. Superwettable hybrid dielectric based multimodal triboelectric nanogenerator with superior durability and efficiency for biomechanical energy and hydropower harvesting. *Chem. Eng. J.* **2022**, *431*, 134002. [CrossRef]
74. Xia, R.; Zhang, R.; Jie, Y.; Zhao, W.; Cao, X.; Wang, Z. Natural cotton-based triboelectric nanogenerator as a self-powered system for efficient use of water and wind energy. *Nano Energy* **2022**, *92*, 106685. [CrossRef]
75. Zhang, S.; Jing, Z.; Wang, X.; Zhu, M.; Yu, X.; Zhu, J.; Cheng, T.; Zhao, H.; Wang, Z.L. Soft-bionic-fishtail structured triboelectric nanogenerator driven by flow-induced vibration for low-velocity water flow energy harvesting. *Nano Res.* **2023**, *16*, 466–472. [CrossRef]
76. Zhang, C.; Dai, K.; Liu, D.; Yi, F.; Wang, X.; Zhu, L.; You, Z. Ultralow Quiescent Power-Consumption Wake-Up Technology Based on the Bionic Triboelectric Nanogenerator. *Adv. Sci.* **2020**, *7*, 2000254. [CrossRef]
77. Wang, J.; Chen, C.C.; Shie, C.Y.; Li, T.T.; Fuh, Y.K. A hybrid sensor for motor tics recognition based on piezoelectric and triboelectric design and fabrication. *Sens. Actuators A Phys.* **2022**, *342*, 113622. [CrossRef]
78. Niu, L.; Peng, X.; Chen, L.; Liu, Q.; Wang, T.; Dong, K.; Pan, H.; Cong, H.; Liu, G.; Jiang, G.; et al. Industrial production of bionic scales knitting fabric-based triboelectric nanogenerator for outdoor rescue and human protection. *Nano Energy* **2022**, *97*, 107168. [CrossRef]
79. Leng, Z.; Zhu, P.; Wang, X.; Wang, Y.; Li, P.; Huang, W.; Li, B.; Jin, R.; Han, N.; Wu, J.; et al. Sebum-Membrane-Inspired Protein-Based Bioprotonic Hydrogel for Artificial Skin and Human-Machine Merging Interface. *Adv. Funct. Mater.* **2023**, *33*, 2211056. [CrossRef]
80. Shi, X.; Wei, Y.; Yan, R.; Hu, L.; Zhi, J.; Tang, B.; Li, Y.; Yao, Z.; Shi, C.; Yu, H.-D.; et al. Leaf surface-microstructure inspired fabrication of fish gelatin-based triboelectric nanogenerator. *Nano Energy* **2023**, *109*, 108231. [CrossRef]
81. Gogurla, N.; Roy, B.; Kim, S. Self-powered artificial skin made of engineered silk protein hydrogel. *Nano Energy* **2020**, *77*, 105242. [CrossRef]
82. Yang, P.; Shi, Y.; Tao, X.; Liu, Z.; Li, S.; Chen, X.; Wang, Z.L. Self-powered virtual olfactory generation system based on bionic fibrous membrane and electrostatic field accelerated evaporation. *EcoMat* **2023**, *5*, e12298. [CrossRef]
83. Xu, Z.; Zhou, F.; Yan, H.; Gao, G.; Li, H.; Li, R.; Chen, T. Anti-freezing organohydrogel triboelectric nanogenerator toward highly efficient and flexible human-machine interaction at −30 °C. *Nano Energy* **2021**, *90*, 106614. [CrossRef]
84. Jin, G.; Sun, Y.; Geng, J.; Yuan, X.; Chen, T.; Liu, H.; Wang, F.; Sun, L. Bioinspired soft caterpillar robot with ultra-stretchable bionic sensors based on functional liquid metal. *Nano Energy* **2021**, *84*, 105896. [CrossRef]