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Review

Recent Advances in Self-Powered Electronic Skin Based on Triboelectric Nanogenerators

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Abstract: Human skin, the body's largest organ, plays a crucial role in perceiving mechanical stimulation and facilitating interaction with the external environment. Leveraging the unique attributes of human skin, electronic skin technology aimed at replicating and surpassing the capabilities of natural skin holds significant promise across various domains, including medical care, motion tracking, and intelligent robotics. In recent research, triboelectric nanogenerators have emerged as a compelling solution for addressing the energy challenge in electronic skins. Triboelectric nanogenerators harness the combination of the triboelectric effect and electrostatic induction to efficiently convert mechanical energy into electrical power, serving as self-powered sensors for electronic skins, which possess the advantages of self-powered operation, cost-effectiveness, and compatibility with a wide range of materials. This review provides an introduction to the working principles and the four operational modes of triboelectric nanogenerators, highlighting the functional features of electronic skins, such as stretchability, self-healing, and degradability. The primary focus is on the current applications of self-powered electronic skins based on triboelectric nanogenerators in medical care, motion tracking, and machine tactile recognition. This review concludes by discussing the anticipated challenges in the future development of self-powered electronic skins based on triboelectric nanogenerators. This review holds practical significance for advancing the practical use of self-powered electronic skins based on triboelectric nanogenerators and offers valuable guidance for individuals interested in pursuing scientific and healthy endeavors.

Keywords: sensors; motion monitoring; tactile recognition; wearable electronic devices

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1. Introduction

Human skin, in addition to its fundamental roles in protection, secretion, and respiration, serves as a vital somatosensory system responsible for human perception, interaction, and communication. The skin's intricate network of tactile receptors allows it to detect external temperature variations and mechanical stimuli, which are subsequently translated into bioelectrical signals transmitted to the brain [1]. Capitalizing on these inherent characteristics and functionalities of human skin, researchers are exploring opportunities to apply electronic skins (e-skins) in various domains. Electronic skin represents a flexible electronic device designed to mimic the properties of human skin. It is crafted from lightweight, transparent, flexible, and stretchable materials, which enable it to be applied to the surface of the human body, facilitating the perception of pressure, temperature, and other external environmental stimuli to create a stimulated sense of touch [2–4]. Due to its flexibility, breathability, sensitivity, and stretchability, electronic skin has garnered significant attention and holds immense potential for diverse applications in human life, spanning wearable electronic devices, human health monitoring, artificial prosthetics, and intelligent robotics [5–8]. Nevertheless, several challenges persist in the widespread integration of electronic skin into human life. One of the most critical obstacles is the issue of energy supply, which is also a fundamental component of modern electronics [9–12].

In the realm of electronic skin, highly sensitive pressure sensors are commonly employed to replicate the mechanical stimuli experienced by the human body. However, many of these sensors rely on external power sources, which can limit their practicality [13,14]. Electrochemical batteries, particularly secondary batteries, are the primary choice for powering electronic devices. While convenient, they have drawbacks, including a limited usage duration, the need for frequent replacement, recharging, and the environmental pollution upon disposal [15–19]. The pursuit of smaller, lighter energy-harvesting technologies that can convert the mechanical energy generated by motion into electricity has led to the exploration of various methods, including the photovoltaic effect [20], the thermoelectric effect [21], the electromagnetic effect [22], the piezoelectric effect [23], and the triboelectric effect [24]. Triboelectric nanogenerators (TENGs), introduced by Professor Wang in 2012, have shown remarkable progress in applications related to human health monitoring and soft robotics in the following years [25–29]. Compared with other nanogenerator-based e-skins, triboelectric nanogenerator-based e-skins have more outstanding properties, including high output performance, low cost, small size, wide range of material choices, and versatility in converting mechanical energy into electrical energy output. It has great potential for energy harvesting and self-powered sensing in wearable electronics [30–34]. Consequently, incorporating TENG principles into electrical skin has proven to be an effective solution for addressing the energy supply challenge. It allows e-skins to harvest energy from the surrounding environment, particularly human motion [35], and simultaneously serve as active sensors that respond to environmental changes by generating electrical signals, such as the voltage or current [33,36–39].

The research results of an e-skin, as a new type of flexible sensor, have brought many benefits to practice. In the medical field, e-skin can be used in medical applications for monitoring the physiological parameters and body states of patients [40–42]. In motion monitoring, it is used to sense and record the body's movement status [43,44]. By placing the e-skin on the desired part of the body, information, such as the body posture, movement amplitude, and movement speed, can be monitored in real time [45]. Finally, e-skin can be applied to smart prosthetics and robots to enable them to sense the external environment more accurately and sensitively. The three aspects are closely related to our daily life, and it is necessary to carry out scientific research in this area under modern conditions [46–48]. Therefore, this review focuses on these three important aspects to explore the latest research progress based on TENG e-skin. This review firstly introduces the principle and working mechanism of triboelectric nanogenerators and secondly introduces several major properties of e-skin, such as flexibility, stretchability, and self-healing. Subsequently, it highlights the unique characteristics of e-skin, including flexibility, stretchability, and self-healing, which enhance its adaptability to various aspects of human life. The review then shifts its focus to the recent advancements in self-powered e-skin applications in healthcare, motion tracking, and robot tactile recognition, as shown in Figure 1 [6,49–65]. Papers on triboelectric nanogenerator-based electronic skin have been summarized over the past five years (Table 1). Lastly, it provides insight into the future development of self-powered e-skin based on TENG and noteworthy challenges to be overcome.

Table 1. Publication statistics for 2019–2023.

Time	Number of Papers about Triboelectric Nanogenerators	Number of Papers about Electronic Skins	Number of Papers about Triboelectric Nanogenerator Based Electronic Skin
2019	652	2126	65
2020	820	2454	38
2021	1220	2912	65
2022	1463	3355	54
2023	1270	2829	42

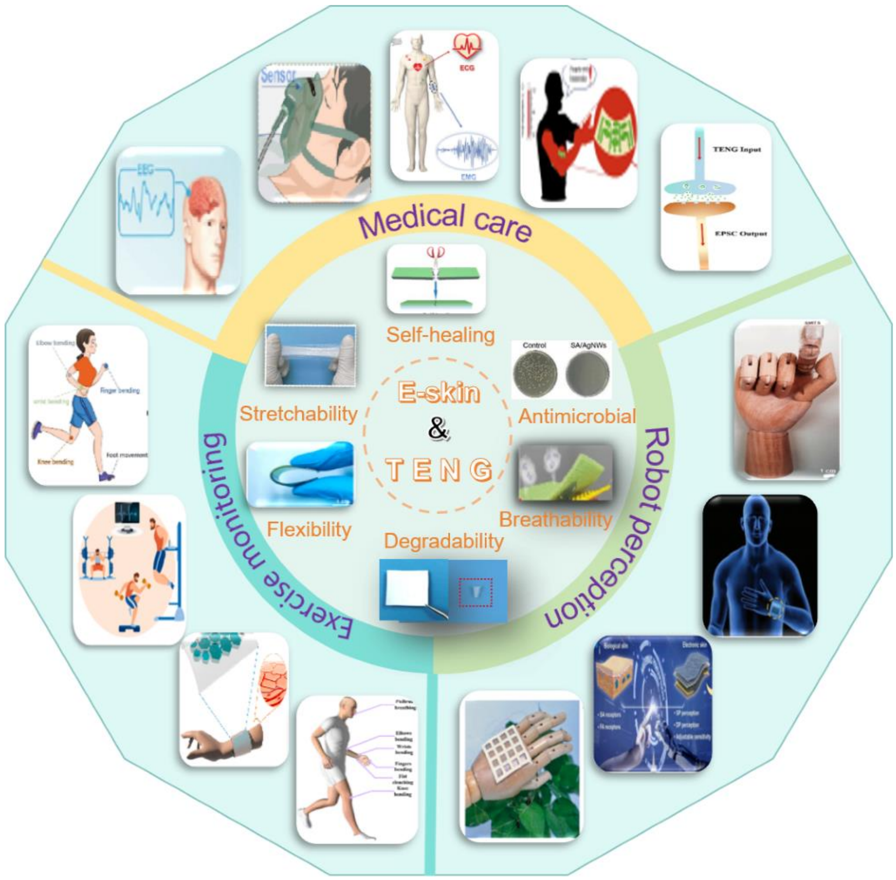

Figure 1. Characteristics of self-powered electronic skin based on a triboelectric nanogenerator and its application in various fields.

2. Basic Principle and Working Mode of Triboelectric Nanogenerators

Since Professor Wang proposed the TENG concept in 2012, it has become an innovative energy-harvesting technology [66]. TENGs work by using the triboelectric effect and the electrostatic induction coupling effect, because when two materials with different electron-binding capabilities rub against each other, different electrons, due to the loss of electron capabilities, will be transferred. The surface of the material generates an opposite equal amount of charge, forming a potential difference between the electrodes, prompting the flow of electrons in the external circuit, thereby generating electrical signals during periodic motion, converting mechanical energy into electrical energy, and generating clean energy. Using Maxwell's equations as a starting point, it has a basic physical model [67]:

$$\nabla \cdot D' = \rho - \nabla \cdot P_s \tag{1}$$

$$\nabla \cdot B = 0 \tag{2}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{3}$$

$$\nabla \times H = J + \frac{\partial D'}{\partial t} + \frac{\partial P_s}{\partial t} \tag{4}$$

Therefore, the selection of friction layer materials and electrode materials, as well as the structural design of TENG, is particularly important, and the friction layer materials are divided into positive and negative electrodes [68]. Common positive materials are nylon, cotton, polyurethane or metal aluminum, copper, etc., and negative materials are PDMS, PVDF, PTFE, and other polymers, while the electrode material is generally selected as a material with excellent electrical conductivity, such as metal, graphite, conductive fibers, etc. [69]. According to different working principles, Professor Wang and his team established four basic working modes of TENG, namely contact-separation mode, lateral sliding mode, single-electrode mode, and freestanding mode [70].

2.1. Contact-Separation Mode

The contact-separated triboelectric nanogenerator is composed of two kinds of triboelectric materials, with electrode material pasted or coated on the back of the triboelectric material to form a circuit between the electrode and the external circuit. According to Figure 2I, if an external force is applied, the surface charges of the two materials will be transferred after contact, and the surface of the electron-losing material will produce an equal amount of positive charge, while the surface of the electronic material will produce the same amount of negative charge. When the external force is cancelled and the triboelectric material is gradually separated due to the existence of electrodes, an electric field will be formed between the triboelectric material to generate a potential difference, which drives electrons to flow in the external circuit to produce electrical signals. When the triboelectric material contacts again, the positive and negative charges on the surface of the material will cancel each other, and the resulting potential difference will disappear, resulting in charge reflux. The electrical signal will be generated in the opposite direction to the external circuit, and the current will be generated by the periodic motion of the TENG.

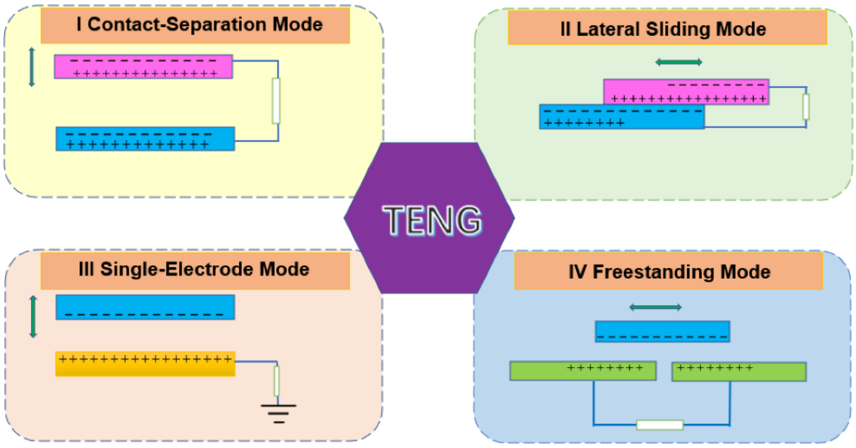

Figure 2. The summary of the basic working modes of a triboelectric nanogenerator. (**I**) Contact-separate mode. (**II**) Lateral-sliding mode. (**III**) Single-electrode mode. (**IV**) Freestanding mode.

2.2. Lateral-Sliding Mode

The lateral sliding mode is mainly based on the friction generated by the translational motion. The two materials in contact with each other do not separate but move with different effective contact areas, as shown in Figure 2II. Triboelectric sliding generates triboelectric charges between two layers of triboelectric materials, resulting in a voltage difference between the electrodes. During this process, the potential difference changes periodically according to the effective contact area, which generates an electric current. In comparison to the contact-separation mode, the lateral sliding mode is more effective at increasing output energy. In addition, the TENG of this type of mode can be used for a variety of environmental movements, such as linear and rotating devices [71].

2.3. Single-Electrode Mode

Both methods mentioned above have two electrodes attached to a moving triboelectric layer, which has caused inconvenience in certain application fields. In order to solve this problem, the single-electrode mode TENG is implemented as shown in Figure 2III. The single-electrode TENG differs from other TENG modes by only having one electrode that directly interacts with the triboelectric layer. The other electrode is merely used as a reference electrode and can be a huge conductor or ground. The working principle of the single-electrode TENG is based on the flow of electrons between the electrode and the ground, resulting in an imbalance in the charge between the two layers. This unbalanced charge can be achieved by sliding or touching, separating the triboelectric layer from the electrode. In addition, the single-electrode TENG structure has shown new avenues in touch sensors and biomedical applications.

2.4. Freestanding Mode

The freestanding mode of TENG is similar to the single-electrode in that it consists of a triboelectric material and two electrodes, while the electrodes are separated from the triboelectric material. As shown in Figure 2IV, when an external force is applied, the triboelectric material first comes into contact with the left electrode, which carries equal amounts of opposite charges. When the triboelectric material slides to the right, the left electrode charge gradually moves to the right electrode, and the charge stored on the right electrode flows to the left electrode through the external circuit, causing the external circuit to generate current. When the triboelectric material is completely coincident with the right electrode, there are left electrode charges on the right electrode. When sliding again, the external circuit charge flows back in the opposite direction, generating a current that is opposite to it. After multiple slides, a current is formed in the external circuit, outputting an electrical signal to the outside. Compared with other modes of TENG, freestanding-mode TENG can achieve relatively a high energy conversion efficiency, which enables it to effectively collect energy in applications, such as human dynamics, self-powered sensors, and airflow measurements [72].

3. Functional Characteristics of Self-Powered Electronic Skin Based on TENG

3.1. Flexibility and Stretchability

Natural skin can stretch and bend freely within a certain range without permanent deformation, which allows the human body to move freely. Similarly, the electronic skin is also exposed to various mechanical stresses and will strain in different directions. Therefore, the flexibility and stretchability of the e-skin are the most important and fundamental characteristics. Due to their skin-like properties, flexible and stretchable electronics have a wide range of demands and great application prospects in the fields of wearable sensing devices, soft robots, and electronic skin. Traditional electronic materials, especially semiconductor materials, whether inorganic or organic materials, are rigid and non-stretchable, and it is difficult to directly apply this to stretchable electronic devices. In order to achieve the mechanical stretchability of materials, special mechanical structures are usually required. For example, out-of-plane folds, in-plane serpentines, island bridges with deformable interconnections, and paper-cut structures can be used to accommodate or eliminate the mechanical strain of non-stretchable materials when they are stretched. However, the method of achieving material stretchability through structural design often has the drawbacks of complex structure, multiple technological processes, and high production costs. Stretchable devices are typically more difficult to make and require new processes and materials compared to flexible electronics, which can be made from ultra-thin plastic substrates. The existing stretchable polymer electronic materials mainly include conductors, elastomers, and semiconductors, which are considered to be promising electronic materials due to their stretchability, ease of processing, and low cost. Therefore, it is possible to construct flexible stretchable devices with simple structures using stretchable polymer electronic materials and have great application prospects [73].

Wang et al. developed a durable and super-stretchable flexible nanogenerator inspired by electric eel-skin for deformable power supplies and fully autonomously compatible electronic skins, as shown in Figure 3a [74]. This device can restore its performance to a strain-free state even after extreme stretching to 300% strain to perfectly capture energy and driving loads. Wu et al. developed a sustainable, shape-adapted, skin-like liquid single-electrode triboelectric nanogenerator (LS-TENG) using aloe vera gel (AVG) @NaCl as a liquid electrode. Figure 3b shows that the LS-TENG can withstand extreme deformation, such as folding, rolling, twisting, and stretching, and its shape and performance can still maintain the initial state after the operation is completed [75]. Li et al. developed a stretchable triboelectric nanogenerator (SH-TENG). The SH-TENG, prepared as shown in Figure 3c, is milky white and has good flexibility [63]. Various mechanical deformations, such as stretching, knotting, and rolling, will not damage the sensing function. Mao et al. reported on an LM electrode, known as Kirigami-structured LM paper (KLP), which produces a multifunctional e-skin that is self-supporting, stretchable, ultra-thin and recyclable. The KLP can also operate as a self-powered e-skin by integrating it with the TENG. According to Figure 3d, stretchable electronics require good electrical stability to transmit signals under various types of deformation [49]. Zhou et al. fabricated a flexible automatic force electronic skin based on a super-stretch triboelectric nanogenerator (STENG) with multilayer thermoplastic polyurethane (TPU)/silver nanowires (Ag NWs)/reduced graphene oxide (rGO) [76]. Figure 3e shows that due to the super-stretch of the TPU fiber pad and the synergistic effect of the multilayer Ag NWs/rGO microstructure, the e-skin exhibits good stability and high tensile properties (200% strain) and still exhibits superior electrical output performance after release. As shown in Figure 3f, Wang et al., inspired by biological cells, developed a soft and retractable TENG as an energy harvesting skin [59]. Under various strains, this TENG can withstand 600% of the strain due to its combination of silicone rubber encapsulation and a triboelectric layer.

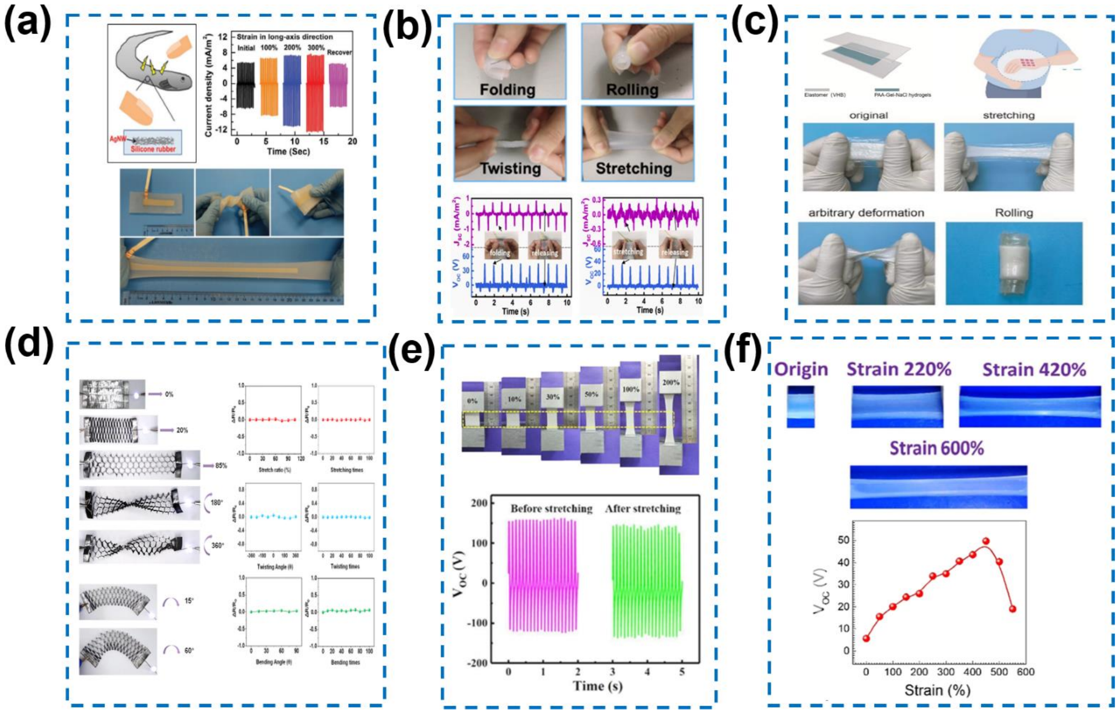

Figure 3. The flexibility and stretchability of e-skin. (**a**) A flexible and ultra-stretched TENG inspired by the skin of the electric eel. Reprinted with permission from ref. [74], Copyright 2016, Wiley. (**b**) A flexible and stretchable single-electrode TENG using aloe vera gel (AVG) @NaCl as a liquid electrode. Reprinted with permission from ref. [75], Copyright 2020, Elsevier. (**c**) A flexible TENG with a stretchability of 800% is used for energy harvesting and tactile perception. Reprinted with permission from ref. [63], Copyright 2021, MDPI. (**d**) A flexible stretchable Kirigami-structured liquid metal paper for multifunctional e-skin. Reprinted with permission from ref. [49], Copyright 2022, American Chemical Society. (**e**) A flexible and self-powered e-skin based on a super-stretchable triboelectric nanogenerator (STENG). Reprinted with permission from ref. [76], Copyright 2020, Elsevier. (**f**) A biologically inspired flexible stretchable TENG e-skin with up to 600% strain. Reprinted with permission from ref. [59], Copyright 2017, Elsevier.

So far, there have been many in-depth studies on the flexibility and stretchability of electronic skin, and significant results have been achieved [31]. The use of flexible and stretchable conductors, semiconductors, stretchable materials, sensors, and substrates has given TENG excellent flexibility and stretchability for self-powered electronic skin, making it advantageous for applications in portable, biocompatible devices. It can also perform its function while adhering to the complex surfaces of human bodies or robots. Although there are more studies on these aspects, as mentioned above, most of the research work on electronic skin diminishes its electrical output performance after a high degree of mechanical external force. Therefore, in order to enable a good response of the e-skin to bending, compression, and tensile strain generation, as well as improved stability of the electrical output properties after multiple stretching, further research is needed. A future investigation in this field will examine the stability of the output performance of triboelectric nanogenerators with self-powered electron skins after multiple stretches.

3.2. Self-Healing and Degradability

The skin of humans and animals has a special ability to self-heal and regenerate after being damaged. In a similar way, triboelectric nanogenerators experience constant external mechanical forces during energy collection and sensing, causing the e-skin to crack or rip; e-skins are severely affected by these factors, which compromise their durability and stability. Existing healing materials for e-skin mainly include polymers, metals, composite materials, and ceramics [77]. According to the different self-healing mechanisms of materials, they can be divided into two categories: firstly, microcapsules containing self-healing agents are doped inside the materials. However, this material has limited self-healing frequency and poor effectiveness and is only suitable for scenarios with single or rare mechanical damage and is not suitable for the field of e-skin. The second is to rely on the dynamic chemical bonds inside the material. When the material is mechanically damaged, the internal chemical bonds will break. Then, they can repair the broken structure through bond recombination and mutual forces to achieve various reversible healings, which is more suitable for the long-term stable working performance of e-skin [78]. Han et al. recorded the self-healing results of polyacrylic gelatin sodium chloride hydrogel (PAA gelatin NaCl hydrogel). Based on the recording of the healing time, Figure 4a shows that the hydrogel can self-heal within 2.5 min after being cut in half [63]. Figure 4b shows that Hu et al. fabricated a triboelectric nanogenerator with an MPP-hydrogel as an electrode (MPP-TENG) [79]. When trying to cut the MPP-hydrogel from top to bottom with a sharp knife, the MPP-hydrogel immediately returned to its original state after removing the blade, without obvious damage or scars. This proves that the MPP-hydrogel can withstand the damage of sharp objects. Cheng et al. prepared a self-healing and durable ionic liquid elastomeric triboelectric generator (ILC-TENG). Figure 4c shows that the performance of ILC-TENG can be restored to its initial state after one and five cutting processes [62]. Cai et al. designed an e-skin based on TENG that can be self-healed within 2 h, and the triboelectric layer of TENG was prepared by adjusting the ratio of imine bonds to hydrogen bonds. The electrode layer is a self-healing conductive composite material prepared through the formation of hydrogen bonds between MXene and lightly crosslinked PDMS. The TENG was cut and repaired once, three times, and five times, and Figure 4d shows no significant change in its triboelectric properties, indicating that the e-skin of the TENG has good multiple repairability [80].

Wearable electronic products based on electronic skins play a crucial role in modern daily life. However, with the rapid development of wearable electronic devices, the amount of electronic waste generated each year is also increasing at an unpredictable rate. How to recycle and dispose of electronic waste is an important issue of global concern. In response to this problem, biodegradable self-powered TENG has attracted attention as a promising energy device in the field of implantable and wearable electronics [81]. Compared to other nanogenerators, biodegradable self-powered TENG can be applied for medical purposes and is also an excellent choice for solving the e-waste problem.

Biodegradability can allow the entire device to be completely or partially degraded by water and soil in the environment, or it can be degraded by pH, light, heat, bacteria, and solvents. This characteristic can reduce the energy sources that produce harmful substances for the environment and organisms and also minimize the cost and risk of recycling electronic waste [82]. Wang et al. developed a self-powered electronic skin based on all-nanofiber TENG using polylactic acid glycolic acid (PLGA) and polyvinyl alcohol (PVA). The synthetic materials PLGA and PVA are well known for their biodegradability. As a comparison, Figure 4e shows in vitro biodegradation experiments on several nanofiber films for up to 50 days, including PVA, PLGA, Ag NWs/PVA, PVA/Ag NWs/PVA, and PLGA/Ag NWs/PVA [64]. As a result of autocatalytic hydrolysis and degradation, PVA weight loss reached 90% after 3 days of incubation, and disappearance almost occurred after 30 days. In contrast, Ag NWs/PVA nanofiber films have a slightly longer degradation cycle due to the presence of Ag NWs, which improve impregnation resistance. There is a high degree of similarity in degradation morphology and weight loss between Ag NWs/PVA and PVA/Ag NWs/PVA nanofiber films, demonstrating that PVA has rapid hydrolysis ability. In the early stages of cultivation, PLGA has good resistance to weight loss and water absorption, but after 30 days of cultivation, the degradation process accelerates dramatically. Figure 4f shows that Gao et al. prepared biodegradable TENG by sticking the chitosan-poly (vinyl alcohol) (CS-PVA) nanofiber film prepared by electrospinning onto a biodegradable magnesium electrode [58]. As shown in Figure 4f, the CS-PVA nanofiber film was soaked in a degradable liquid (acetic acid in this study), and it was found that the fiber film curled after soaking for 1 h at room temperature. With an increase in the soaking time, the curl degree of the CS-PVA nanofiber film became larger and thinner and gradually became more transparent. Finally, it was completely degraded within 3 days, showing its good degradability. Similarly, in Figure 4g, Peng et al. also made a kind of e-skin based on TENG with chitosan and conducted an in vitro biodegradation study [83]. As a result of immersion in various media, such as acid solution, hydrogen peroxide solution, and enzyme solution, it proved to be extremely degradable and excellent at degrading.

Therefore, electronic skins based on TENG with self-healing abilities are particularly important for applications in a wider range of fields. However, the self-healing ability of existing electronic skins based on TENG mostly needs to be achieved under certain conditions, such as higher temperatures or longer time conditions, and few can achieve self-healing without additional conditions [84]. Next, we should focus on the research of electronic skin devices that can self-heal without the need for additional external conditions. In addition, the destruction of natural resources and environmental pollution are increasingly serious, and e-skin devices with biodegradability are particularly important for protecting the environment. At this stage, there are not many degradable materials that have been explored. In the next step, we should also explore more environmentally friendly, stable performance and degradable materials that can be applied to TENG-based electronic skin from the perspective of environmental protection, which is conducive to developing more degradable electronic skin wearable devices based on TENG in accordance with the era of a green economy.

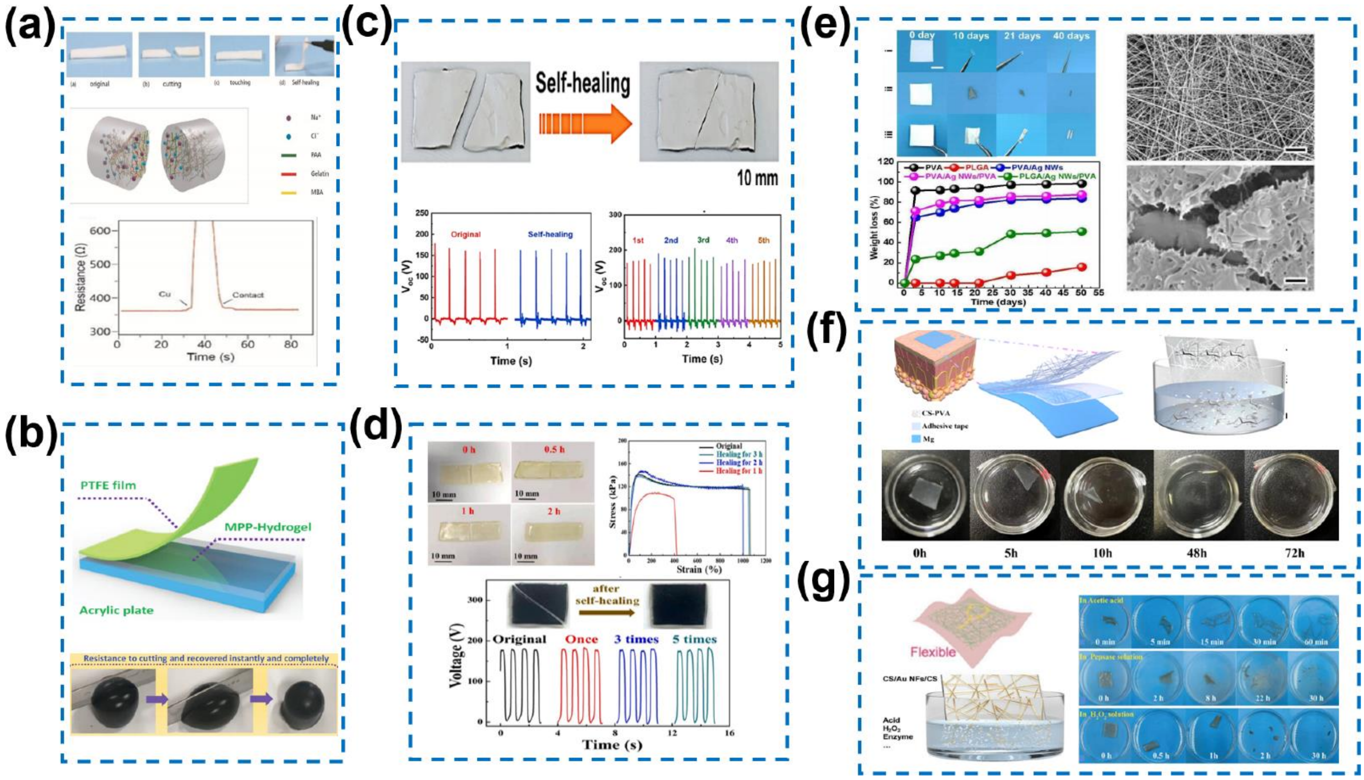

Figure 4. The self-healing and degradability of e-skin. (**a**) A single-electrode TENG e-skin that can achieve self-healing within 2.5 min at room temperature. Reprinted with permission from ref. [63], Copyright 2021, MDPI. (**b**) A healing ionic liquid elastic matrix TENG e-skin. Reprinted with permission from ref. [79], Copyright 2022, Wiley. (**c**) The use of an MPP-water gel as a TENG electrode can realize self-healing after cutting. Reprinted with permission from ref. [62], Copyright 2022, Elsevier. (**d**) A self-healable TENG based on double-cross-linked PDMS for the e-skin. Reprinted with permission from ref. [80], Copyright 2022, Elsevier. (**e**) A biodegradable self-powered e-skin based on an all-nanofiber TENG. Reprinted with permission from ref. [64], Copyright 2020, Amer Assoc Advancement Science. (**f**) A biodegradable TENG based on chitosan. Reprinted with permission from ref. [58], Copyright 2023, American Chemical Society. (**g**) A degradable self-powered e-skin integrated with a single-electrode TENG. Reprinted with permission from ref. [83], Copyright 2022, Wiley.

3.3. Breathability and Antibacterial Properties

As far as electronics that are in direct contact with the human skin are concerned, we are foremost concerned with the comfort and abrasion resistance of the products. This is achieved mainly through their flexibility, stretchability, breathability, and moisture permeability. For electronic skin that is used to fit the human skin for exercise or health monitoring, the human body produces sweat and other fluids that are excreted through the skin to achieve a moisture–heat balance and maintain normal working conditions. As a fabric that exchanges air and moisture between the skin and its environment, breathability is important for regulating and maintaining the thermal balance of the human body's surface microenvironment [85]. Based on this requirement, Wang et al. designed an e-skin with a micro-nano-layered porous structure, as shown in Figure 5a, which has a high contact charge-specific surface area and a large number of capillary channels, making it easy for gas and water molecules to be transported through channels between fibers for the transfer of moisture and heat between human skin and the environment [64]. Yue et al. designed a breathable e-skin with a multi-layer nanofiber structure (B-C-N PVA/PVDF NFs) inspired by spider webs and ant tentacles, as shown in Figure 5b [86]. Thanks to the complete nanofiber structure, the e-skin is breathable to 20.87 mmS^{-1}, ensuring comfort when wearing the e-skin. Aside from their moderate hydrophobicity (a water contact angle of 94.3°), B-C-N PVA/PVDF NFs also ensure comfort for humans wearing electronic skin. The skin structure of the electronic skin is also protected from sweat damage. Figure 5c shows that Kar et al. reported a novel breathable e-skin made of chicken feather fiber (CFF) and a PVDF polymer composite [87]. In this study, a sample of 5 wt% CFF material was added to PVDF as a functional layer of PCFF. The water vapor transmittance (WVT) of PCFF was compared with PVDF and tissue, and the results showed that PCFF had a higher WVT rate (~12 kg $m^{-2}day^{-1}$). Therefore, the good breathability of PCFF confirms its applicability in the manufacturing of wearable electronic devices.

The majority of high-performance e-skins use cell membranes as electrodes or substrates, which can irritate the body's natural skin and make it itchy [88]. Therefore, antimicrobial properties are an important performance optimization for e-skins to inhibit bacterial growth and prevent bacterial infections. For antibacterial properties, silver material is a very suitable choice. For a wide range of medical applications, silver is the most promising antibacterial drug because of its biocidal properties for bacteria, fungi, and viruses [89]. According to Zhu et al., layered nanostructures, inspired by the microstructure of rose petals, can be prepared using a special "replication" method. Subsequently, the bacteriostatic properties were investigated using Gram-negative *Escherichia coli* (*E. coli*) and Gram-positive *Bacillus subtilis* (*B. subtilis*). From Figure 5d, it can be seen that PDMS substrates with different antibacterial agent contents have significant antibacterial activity, and the antibacterial effect of PDMS on *E. coli* and *B. subtilis* is enhanced with an increase in the antibacterial components [90]. According to Wang et al., a TENG electronic skin was created using a silver nanowire electrode sandwiched between a TPU sensing layer and a PVA/CS substrate, and the antibacterial effects of this substance were significant against *E. coli* and *Staphylococcus aureus* (*S. aureus*). As shown in Figure 5e, the antibacterial performance was tested using (i) TPU, (ii) PVA/CS, and (iii) e-skin with initial diameters of 1 cm [91]. After 24 h of cultivation, pure TPU showed no antibacterial activity against both bacteria, while PVA/CS showed good antibacterial activity against *E. coli* and *S. aureus*, with inhibition zone diameters of 1.175 cm and 1.283 cm, respectively. Among the most noteworthy features is a large inhibition zone around the e-skin, for which the diameter against *E. coli* and *S. aureus* was 1.379 cm and 1.237 cm, respectively. This phenomenon further concludes that the synergistic antibacterial effect between CS and Ag NWs results in significant antibacterial performance of the e-skin. As shown in Figure 5f, Yan et al. established a multi-layer nanofiber membrane electronic skin with a double gradient by modifying the cations and anions of poly ionic liquids (PILs) and using the spinning process [51]. In order to evaluate the antibacterial activity of the electronic skin, Gram-negative *Escherichia coli* and Gram-positive *S. aureus* were selected to study the antibacterial activity of the PIL membrane using various methods. As shown in Figure 5f, the PIL film killed most of the bacteria within only 2 h, and all of the active colonies of the studied microorganisms almost completely disappeared after 4 h of cultivation, with a bacteriostatic rate of more than 99%, and the diameter of the inhibition zone was 10 mm and 9.4 mm, respectively, demonstrating superior antibacterial properties.

All in all, the two characteristics of breathability and antibacterial are beneficial for TENG-based e-skin to be more closely applied to human skin for various monitoring purposes. However, most of the current research focuses on the stretchability or other output properties of the e-skin, and there are few studies on the breathability and antibacterial properties of the e-skin. In addition, most of the research experiments on the antibacterial properties of the e-skin used *E. coli* and *S. aureus*, which are difficult to obtain and harmful to the human body, require strict environmental conditions, and very easily cause infection if improperly operated. Therefore, the next step is to find other non-toxic and easy-to-operate bacteria to conduct antibacterial experiments on electronic skin, such as yeast and lactic acid bacteria.

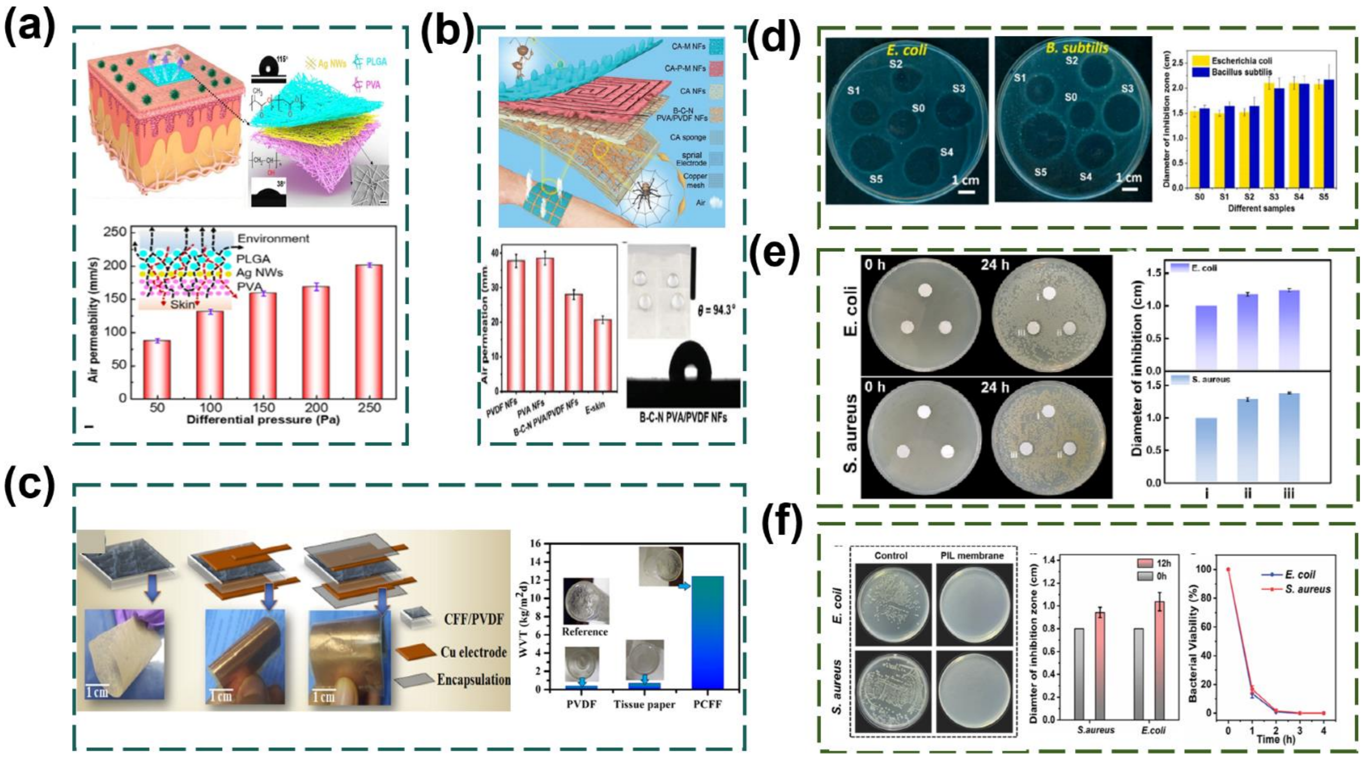

Figure 5. Permeability and antibacterial properties of e-skin. (**a**) A breathable e-skin with a micro/nano-layered porous structure. Reprinted with permission from ref. [64], Copyright 2020, Amer Assoc Advancement Science. (**b**) A breathable e-skin with a nanofiber structure inspired by spider webs and ant tentacles. Reprinted with permission from ref. [86], Copyright 2021, Wiley. (**c**) A novel breathable e-skin made of feather and a PVDF polymer composite material. Reprinted with permission from ref. [87], Copyright 2023, American Chemical Society. (**d**) An antibacterial e-skin inspired by the microscopic structure of rose petals. Reprinted with permission from ref. [90], Copyright 2021, Elsevier. (**e**) An antibacterial TENG e-skin fabricated by sandwiching Ag NWs between TPU and PVA/CS. Photographs of the inhibition zone of (**i**) TPU, (**ii**) PVA/CS, and (**iii**) E-skin before and after incubating for 24 h. Reprinted with permission from ref. [91], Copyright 2021, American Chemical Society. (**f**) An antibacterial electronic skin based on a double-gradient poly (ionic liquid) nanofiber membrane. Reprinted with permission from ref. [51], Copyright 2021, Wiley.

4. Practical Application of Self-Powered Electronic Skin Based on a Triboelectric Nanogenerator

4.1. Application of Self-Powered Electronic Skin Based on TENG in Healthcare

With the increasing aging population, social welfare and healthcare have brought a heavy burden to the socio-economic system [92]. Real-time monitoring can provide physiological signals related to human health, such as pulse, heart rate, vocalization, respiratory rate, etc., which is of great significance for preventing, diagnosing, and treating diseases. Healthcare electronics help people effectively treat and monitor disease in real time, and electronic skin based on triboelectric nanogenerators (TENGs) shows great potential in healthcare applications [93]. As shown in Figure 6a, Yu et al. reported a contact separation triboelectric nanogenerator (CS-TENG) consisting of an ultra-flexible micro-resistance-array polydimethylsiloxane (mf-PDMS) film and Cu electrode as the basic triboelectric unit [94]. The CS-TENG can sense the subtle changes in wrist pulse under various physiological conditions, simulate the collection of three finger pulses in traditional Chinese medicine, and achieve conformal contact with irregular human skin, so as to realize self-powered monitoring of weak physiological signals of the human body very comfortably. Figure 6b shows a novel self-powered temperature-sensitive e-skin prepared by Liu et al.

using patterned polydimethylsiloxane/polyaniline (PDMS/PANI) nanostructures, which can monitor body temperature in real-time [52]. This study attached the e-skin to a human arm joint and simply demonstrated the practical application of temperature-sensitive e-skin to detect body temperature without external power. Driven by arm bending, the triboelectric output of e-skin at a normal body temperature (36.6 °C) and high temperature (42.0 °C) was approximately 10.25 nA and 13.04 nA, respectively. Using this method, it is feasible to monitor body temperature in real-time, and multifunctional wearable sensors and nano-systems can be developed. Breathing is the most basic physiological behavior of the human body, and it is also an important evaluation index for evaluating human health. As shown in Figure 6c, Peng et al. designed a breathable, highly sensitive, and self-powered e-skin based on TENG for real-time respiratory monitoring and the diagnosis of obstructive sleep apnea hypopnea syndrome (OSAHS) [95]. In order to assess the severity of OSAHS, it is necessary to conduct a further real-time analysis of respiratory signals. Therefore, the all-nanofiber self-powered electronic skin designed in this study for spontaneous breathing detection provides a simple, non-invasive detection method. In addition to improving sleep quality and human respiratory health, this helps to monitor OSAHS and prevent other complications. Gogurla et al. proposed an e-tattoo that is composed of carbon nanotubes (CNTs) and silk nanofibers (SNFs) as an unlined substrate, skin-compatible, skin-adhesive, deformable, and mechanically deformable. The TENG electronic tattoo can be used as a self-actuated sensory system to monitor physical conditions in a real-time, continuous, and non-invasive manner. As shown in Figure 6d, sticking it to the throat can monitor the sound signals emitted by the human body, which may help deaf and mute people recognize sounds in the future [96]. Studies have shown that wearable TENG is able to generate an electric field locally in the wound, thereby accelerating wound healing. As shown in Figure 6e, Du et al. demonstrated an e-skin based on single-electrode TENG (NIR + TENG) that promotes wound healing by synergistically utilizing electrical stimulation and photothermal heating capabilities [97]. The controlled experiment designed in the figure shows that NIR + TENG has the fastest and best effect in promoting wound recovery, and extending the treatment time of NIR + TENG can further accelerate wound closure. These results all indicate that NIR + TENG has a first-class therapeutic effect in promoting wound healing. Figure 6f shows an LS-TENG device that can detect subtle facial expressions in the human body [75]. The device exhibits high sensitivity to subtle facial expressions and is suitable for manufacturing 2D or 3D shapes, indicating its enormous potential in wearable electronic devices, such as electronic skin and health monitoring. The self-powered synaptic transistor (SPST) was developed by Liu et al. in 2019. The voltage was provided by a triboelectric nanogenerator, without the use of additional voltage, to generate presynaptic spikes, as shown in Figure 6g [53]. With the increasingly severe trend in global aging, the health of the elderly is of great concern. Falling is the most common risky behavior in the daily life of the elderly. As shown in Figure 6h, Yin et al. reported a hybrid electronic skin (CNES) that realizes contact and non-contact sensing, which includes a TENG and a flexible humidity sensor layer to monitor the fall behavior of the elderly [98]. During the experiment, the device did not emit alarm signals or emergency calls when the volunteers were standing, sitting, or even standing up from their seats. Alarm signals and emergency calls only occur when volunteers fall to the ground, demonstrating the feasibility of CNES in monitoring human fall behavior.

Currently, part of the focus of TENG-based self-powered electronic skin in healthcare is to monitor physiological signals. such as respiration, pulse, temperature, and sound, to determine the health status of the body. Another part is used for medical equipment, such as intelligent prosthetics, artificial synapses, and wound treatment [99]. However, the accuracy and timeliness of real-time data acquisition for monitoring human health status still need to be further improved, and the next step can focus on the visualization of monitoring data so that users can understand their own information in real time for prevention and health care. In addition, a more important point is the privacy and security of the user, an aspect that has rarely been reported in studies. E-skin can collect and transmit individual physiological data, which could potentially raise concerns about privacy and security. How to protect the security and privacy of data is also an important consideration.

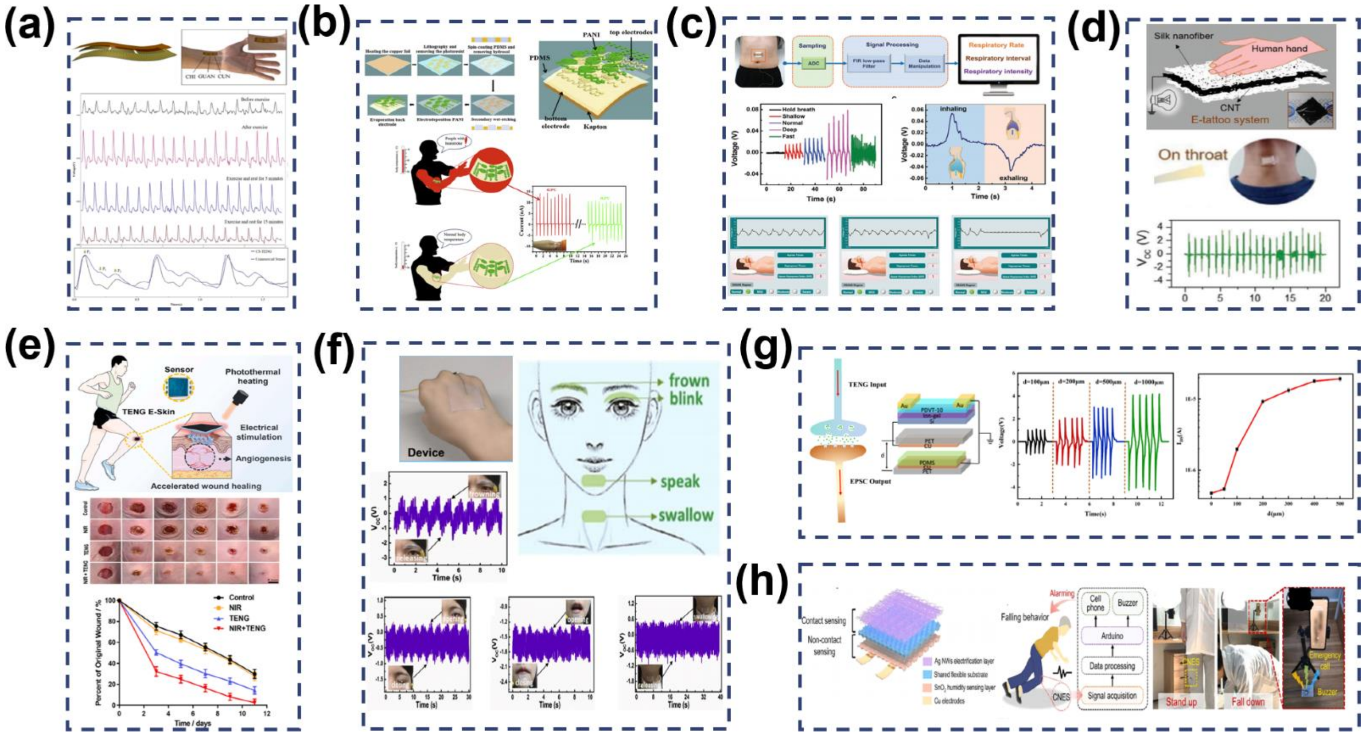

Figure 6. Application of TENG e-skin in healthcare. (**a**) A triboelectric e-skin that can monitor physiological signals. Reprinted with permission from ref. [94], Copyright 2020, Elsevier. (**b**) A self-powered temperature-sensitive electronic skin based on the triboelectric effect of PDMS/PANI nanostructures. Reprinted with permission from ref. [52], Copyright 2019, Elsevier. (**c**) A self-powered e-skin based on TENG for the real-time monitoring of respiration and sleep. Reprinted with permission from ref. [95], Copyright 2021, Wiley. (**d**) A self-powered invisible electronic tattoo sticker that detects sound. Reprinted with permission from ref. [96], Copyright 2021, Wiley. (**e**) A self-powered and photothermal e-skin patches for accelerating wound healing. Reprinted with permission from ref. [97], Copyright 2022, Elsevier. (**f**) A liquid single-electrode TENG can monitor tiny facial expressions. Reprinted with permission from ref. [75], Copyright 2020, Elsevier. (**g**) A self-powered artificial synapse was developed based on TENG. Reprinted with permission from ref. [53], Copyright 2019, Elsevier. (**h**) A hybrid e-skin combining TENG and humidity sensors detects fall behavior. Reprinted with permission from ref. [98], Copyright 2022, Elsevier.

4.2. Application of Self-Powered Electronic Skin Based on TENG in Motion Monitoring

Affected by COVID-19, more and more people are aware of the importance of sports for health. Physical exercise can enhance the body's resistance, cultivate people's reaction ability and sensitivity, and enhance the body's ability to adapt to the external environment [100]. Scientific exercise is beneficial to human health, while improper exercise can be harmful. Therefore, it is particularly important to monitor physical activity and health indicators during exercise. The TENG-based self-powered electronic skin converts the mechanical energy generated by human movement into electrical energy, so as to detect the state of the human body during exercise, provide exercise information, and avoid sports injuries [72]. Due to the fact that human sweat with implicit physiological information has been considered an easily accessible way to detect personal health status, as shown in Figure 7a [101], He and his colleagues designed an electronic skin capable of analyzing sweat in real-time during human movement. To detect urea, uric acid, lactic acid, glucose, Na^+, and K^+ concentrations in sweat, this electronic skin can be attached to the human body without any external power source. The electronic skin can be connected to a visualization panel, and the input triboelectric current can show the motion state of the human body while it is in motion. Similarly, Zhao et al. also proposed a self-powered biosensing e-skin for real-time sweat Ca^{2+} detection and wireless data transmission. Self-powered electric skins can capture small mechanical energies from human movement and output biosensing signals directly, with the triboelectric current of the output current depending on the Ca^{2+} concentration in sweat. As shown in Figure 7b, this electronic skin can be attached to the knee, which can be easily driven by the knee during exercise and detect the Ca^{2+} concentration in sweat without any external power [102]. Figure 7c is a self-powered, stretchable, and fiber-based electronic skin developed by Fu et al. for the active detection of various human movements and atmospheric environments, such as finger touch, joint movement, skin deformation, and slight stretching [103]. This electronic skin is woven from carbon fiber bundles coated with PDMS and Ppy, and the measurement mapping matrices generated by middle finger and fist movements are shown in the Figure 7c, which can be observed and easily recognized. These results indicate that the self-powered electronic skin can monitor human movement and has potential application prospects in tactile perception. In Figure 7d, Wei and his coworkers reported a hybrid electronic skin (PTES) composed of a triboelectric nanogenerator and piezoresistive pressure sensor that can perceive static and dynamic tactile information with high sensitivity, such as human physiological information, the tactile sensation of the manipulator, and the human walking state [56]. By combining PTES with a high-speed data collector and machine learning, a material sensing system capable of recognizing 12 materials in real time was created. As shown in the Figure 7d, the walking state of the human body can be monitored by placing PTES on the sole of the foot, including functions, such as slow walking, fast walking, and abnormal walking. The slow or fast walking state of a normal person is shown by the red line in Figure 7d. Considering that for people with leg disabilities, the contact time between the soles of the feet and the ground is longer and the force during walking is uneven, the state is shown by the blue line in the figure. Song et al. also developed a multi-functional and highly robust electronic skin (FOSE-skin) that operates independently. Figure 7e shows the output current of the TENG-based FOSE-skin in detecting interphalangeal and metacarpophalangeal joint movements [104]. There is a high output current generated by the movement of the metacarpophalangeal joints because of the large area of contact between the metacarpophalangeal joints and the FOSE skin. As shown in Figure 7f, Shi et al. report an e-skin with a triboelectric nanogenerator for self-powered volleyball reception analysis and statistics [91]. It is made by sandwiching silver nanowire (Ag NW) electrodes between a thermoplastic polyurethane (TPU) sensing layer and a polyvinyl alcohol/chitosan (PVA/CS) substrate. In response to the signal from a volleyball player, the ball strikes both pixels with both arms at the same impact position, and the electronic skin produces a signal that is distinctly identical to that of the volleyball player. Then, a multi-channel output voltage measurement is performed to simultaneously detect the voltage signal of each sensing pixel. In the program, the statistics and analysis results can be obtained after signal processing, which allows for the volleyball's receiving speed to be judged and the effect to be received in real time. Similarly, a triboelectric nanogenerator fabricated using electrospinning and spraying techniques, as shown in Figure 7g, has been developed by Shi et al. [105]. Electrospinning and spraying techniques are used to deposit a silver nanowire (Ag NW) electrode layer between two electrospinning thermoplastic polyurethane (TPU) fiber layers. In order to monitor different parts of the human body in real time, this e-skin is attached to the elbow (i), fingers (ii), wrist (iii), and legs (iv). As a result of the different pressures obtained from different parts of the human body, different voltage signals will be reflected by these electronic skins during exercise. It is anticipated that these electronic skins will be used in the next generation of electronics, including artificial intelligence, flexible robotics, and multi-dimensional motion monitoring.

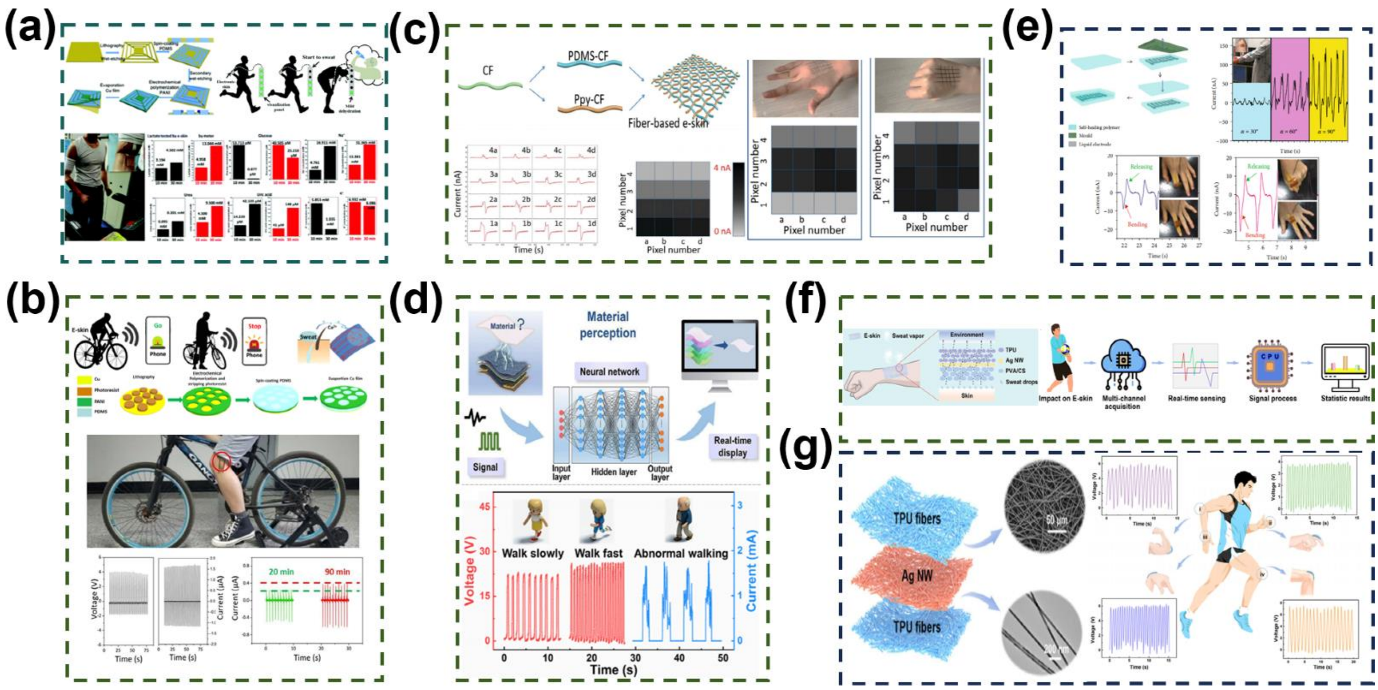

Figure 7. Application of TENG e-skin in exercise monitoring. (**a**) An e-skin that allows for real-time perspiration analysis and movement status monitoring. Reprinted with permission from ref. [101], Copyright 2018, Royal Society of Chemistry. (**b**) E-skin for real-time perspiration analysis under motion-state monitoring. Reprinted with permission from ref. [102], Copyright 2019, IOP Publishing LTD. (**c**) An e-skin that can detect finger joint movement based on fiber fabric. Reprinted with permission from ref. [103], Copyright 2017, Royal Society of Chemistry. (**d**) An e-skin that can monitor different walking states. Reprinted with permission from ref. [56], Copyright 2022, Elsevier. (**e**) An e-skin based on TENG that can monitor arm swing. Reprinted with permission from ref. [104], Copyright 2022, Amer Assoc Advancement Science. (**f**) A self-powered e-skin for volleyball receiving statistics and analysis. Reprinted with permission from ref. [91], Copyright 2021, American Chemical Society. (**g**) A TENG e-skin for human motion monitoring. Reprinted with permission from ref. [105], Copyright 2022, MDPI.

Up to now, the self-powered electronic skin of TENG has been widely used in the training monitoring of human movement through the collection of movement information and feedback to solve the problems encountered in the complex environment of human movement training and to meet the needs of different sports groups for the intelligent monitoring of movement. In the digital era today, TENG has achieved the collection of sports information and started digital sports monitoring. Therefore, the self-powered electronic skin based on TENG can be comfortably worn on the human body to reflect the real changes in movement, select the appropriate training intensity and improve training efficiency.

4.3. Application of Self-Powered Electronic Skin Based on TENG in Machine Tactile Recognition

Nowadays, the application of robots in various industries is developing from mechanization to automation, intelligence, and precision, and tactile perception is a key element for robot technology to achieve agile operation and safe human–machine interactions [106]. In the same way as human skin perceives shapes, hardness, textures, and slip while operating, tactile sensors are able to detect such properties as shape and hardness using tactile sensors [107]. In order to simulate the tactile perception ability and mechanical properties of human skin so that robots can perceive external things like human skin, people have carried out much research on the development of electronic skin. E-skin based on TENG has gained widespread applications and has enormous potential in fine texture recognition. As shown in Figure 8a, Lee et al. reported the first approach for implementing stretchable multimodal devices, which are based on various electrical properties, such as piezoelectric, triboelectric, and piezoresistive properties, with the dielectric layer exhibiting surface roughness that mimics human fingerprints [108]. The simultaneous perception and analysis of integrated stimuli can enable multifunctional e-skins to perform the material recognition and texture recognition of bionic prostheses when applied to a robotic hand. The authors attached the e-skin to a robotic hand to sense a variety of materials, each with different properties, such as roughness, surface energy, and surface charge density. The e-skin device classified materials with $84.4 \pm 0.4\%$ accuracy from texture information collected by the sensors, compared to $62.2 \pm 0.5\%$ for human skin. The results suggest that this multifunctional e-skin can be used as a sensory organ in robotic prostheses with tactile perception similar to or better than that of humans. Similarly, Zhao et al. have also been inspired by fingerprints to build a TENG-based electronic skin (FE-skin) that can respond to fine textures through the bionic design of human fingerprint morphology. FE-skin can detect changes in the contact area caused by the dynamic interaction between the fingerprint structure and the surface of the measured object, and the minimum recognizable texture size is as small as 6.5 μm. In addition, as shown in Figure 8d, the study also applied Braille to test FE-skin [109]. There is evidence that Braille recognition helps humans recognize fine texture on objects, including the fine, tactile perception of fingertip skin and the brain's ability to reconstruct texture distribution rapidly. Figure 8b shows the tactile sensor based on a double-layer single electrode reported by Lin et al., which is independent of the contact material used for robot perception [110]. By integrating the device into the palm of the robot's hand, the tactile perception of objects made of any material was successfully demonstrated, as well as the potential human–computer interaction function as a robotic electronic skin. As shown in the figure, six typical materials were selected, including skin, wood, glass, metal iron, fabric, and plastic, to click on the sensor array to test its applicability. It can be clearly seen that all six materials can generate voltage output, and the output performance remains consistent in size, indicating the universal applicability of sensor arrays as robot electronic skins. Based on single-electrode-mode triboelectric nanogenerators (S-TENGs), Wang et al. proposed a fully elastic multi-dimensional sensor electronic skin capable of sensing both normal and shear forces, as shown in Figure 8c [111]. Using an experimental setup for robot grasping recognition, the researcher tested the usefulness of the sensors in practical applications. On the fingers of the robot arm, there are two sensors that measure shear force. By adjusting the height of the lifting platform, the shear force can be measured and recorded. Figure 8c shows the normal and shear forces detected by the sensor throughout the entire process, indicating that the sensor has great potential for robot tactile perception and object recognition. Chen et al. developed an energy-assisted e-skin that can directly sense temperature and pressure, as shown in Figure 8e [112]. In this way, temperature and pressure stimuli are converted into two separate voltage signals without interfering with each other. At a pressure of 0–100 kPa, when different temperature differences are applied to the device, the thermoelectric voltage output remains constant, indicating that pressure does not interfere with its operation. In addition, the application of temperature and pressure integration technology in a human–machine interaction (HMI) scene simulation was also discussed. E-skin sensors were attached to the robot's palm to sense temperature and pressure when picking up a cup of water. The corresponding temperature and pressure signals are shown in Figure 8e. As a result of its precision in measuring micromotions and temperature changes, as well as its good consistency of sensing signals, the e-skin sensor can be used for robot technology and human-machine interfaces. Figure 8f shows a stretchable dual-mode sensor array designed by Zhang et al. for multifunctional robot electronic skin [113]. To achieve the tactile perception of bionic hands, liquid metal electrodes can be used in the capacitive mode or triboelectric nanogenerator mode with electronic skin sensors. Sensor arrays in this dual-mode design were integrated into bionic hands to validate their uses as robotic electronic skins. As a result, 9.4 kPa of pressure was applied to the thumb and 8 kPa to the middle finger. Therefore, the electronic skin sensor array can be used as an electronic skin for biomimetic hands to achieve tactile perception. Because it is easy to design and manufacture, this electronic skin sensor array has great application prospects in operation, repair, and service robot recognition technology.

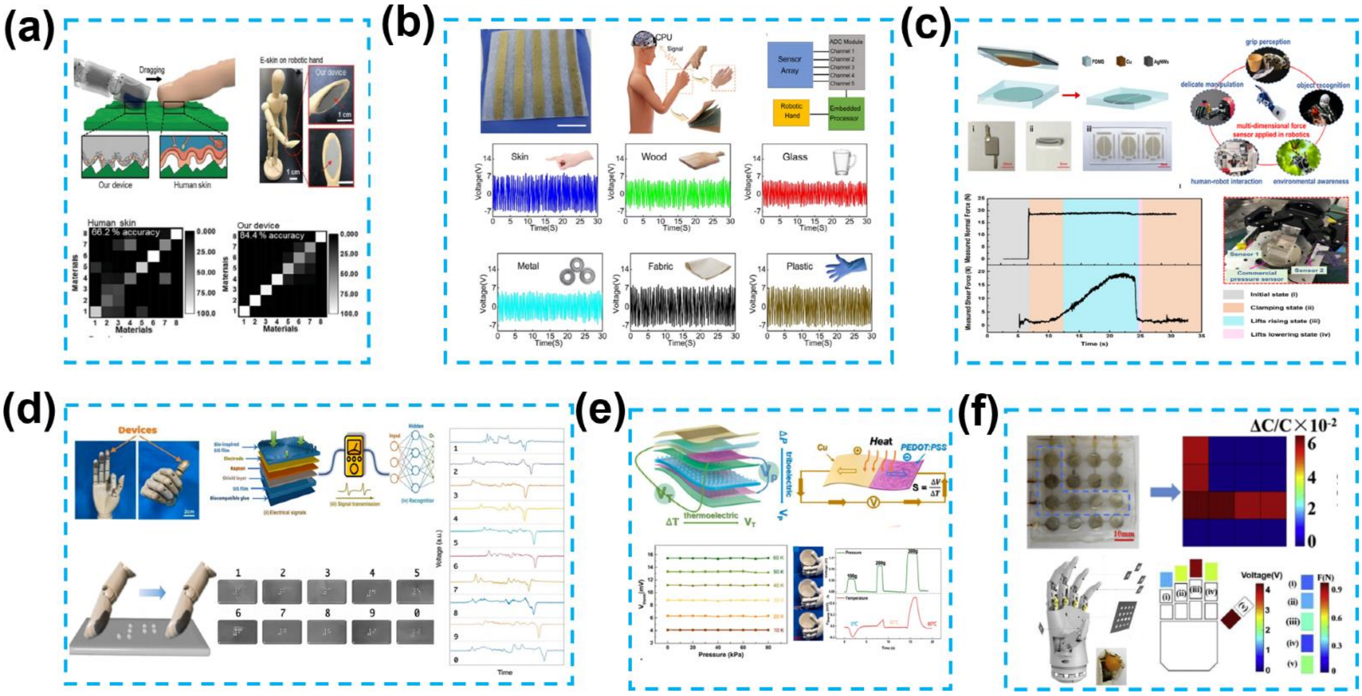

Figure 8. Application of TENG electronic skin in robot recognition technology. (**a**) A multimodal e-skin for robotic material and texture recognition. Reprinted with permission from ref. [108], Copyright 2021, Wiley. (**b**) A TENG e-skin for robot intelligent perception and interaction technology. Reprinted with permission from ref. [110], Copyright 2021, Wiley. (**c**) A multi-dimensional force sensor electronic skin for robot recognition technology. Reprinted with permission from ref. [111], Copyright 2022, American Chemical Society. (**d**) A kind of fine texture recognition for robot TENG e-skin. Reprinted with permission from ref. [109], Copyright 2021, Elsevier. (**e**) An e-skin that can be used for robot temperature–pressure-sensing functions. Reprinted with permission from ref. [112], Copyright 2022, Elsevier. (**f**) A dual-mode sensor array for multifunctional robot e-skin. Reprinted with permission from ref. [113], Copyright 2019, Elsevier.

The original research motivation of electronic skin is to understand biological perception, and the research on the excellent perception abilities of soft robots and artificial robots is becoming more and more in-depth. Existing drawbacks include poor resolution, a lack of dynamic responsiveness, and integration difficulties. It is hoped that the lessons learned in the course of the research can help to address these drawbacks and improve the design of robotic systems to enhance tactile recognition, pressure sensing, and the intelligent analysis of robots [114–117]. In the next step, the self-powered electronic skin based on TENG can be used in robotic applications to achieve thinner and lighter simulation, more sensitive and favorable tactile sensing, and improvements in resolution and integration, which will help to open up a wider space for the next development of robotic tactile recognition capabilities.

5. Conclusions and Outlook

The rapid evolution of modern society and living standards, particularly in the aftermath of the COVID-19 pandemic, has spurred a growing demand for intelligent devices capable of monitoring human physiological signals and physical activities [118–121]. Consequently, wearable devices for human body monitoring have emerged as a pivotal direction in the future scientific and technological development [45–48,73,122,123]. The significance of the research on e-skin is that it provides more possibilities for various industries, makes human–computer interactions more intelligent and natural, and improves the quality of life and work efficiency of human beings. The development of e-skin will promote the innovation and progress of various industries. This review examines the latest developments in the development of self-powered e-skins based on TENG, emphasizing the advantages of each component and its primary applications. Our first step was to explain the four modes of operation for TENG, namely contact-separation mode, lateral-sliding mode, and single-electrode mode. Subsequently, we underscored the attributes of electronic skin, such as flexibility, stretchability, self-healing, degradability, and antibacterial properties and breathability, which render it suitable for use in wearable electronic devices and robot tactile recognition. Looking forward, electronic skin is expected to become further miniaturized, thinner, more seamlessly integrated, and more intelligent in its sensing capabilities. Furthermore, the recent advancements in self-powered electronic skin based on TENG were elucidated, highlighting its evolving role in various domains, including healthcare, human motion monitoring, and robot tactile recognition. These developments underscore the substantial potential of TENG-based electronic skin. While research on electronic skin is advancing at a rapid pace, challenges persist, particularly in the development of electronic skin powered by triboelectricity. As shown in Figure 9, several of these challenges and opportunities are outlined below:

1. Manufacturing process. The manufacturing process for electronic skins is often complex due to the numerous performance requirements that they must meet. Additionally, many self-powered electronic skins based on TENG necessitate the synthesis and structural design of chemical materials to accommodate diverse applications. Therefore, research into methods that can simplify the manufacturing process while retaining the various characteristics of electronic skin is essential. Furthermore, cost-efficiency and low energy consumption are crucial advantages in manufacturing technology, especially with TENG's ability to harness mechanical energy from the surrounding environment [124]. Research should continue to explore ways to reduce costs and energy consumption in the design and production of electronic skins based on TENG, including the use of recyclable materials as primary components.
2. Multifunction monitoring. Recent studies have primarily focused on improving electronic skin's tactile perception, intelligent recognition, and human health monitoring. While these are essential functions, there is an opportunity to enhance e-skin's ability to perceive the surrounding environment and ensure user safety. This includes the integration of safety-related information into self-powered TENG-based e-skins for preventative purposes. Additionally, the growing momentum in visual technology presents an opportunity to integrate TENG energy-collection capabilities with electronic skins, offer increased power output and a more realistic user experience, thereby supporting a broader range of monitoring functions. Therefore, when future e-skins are capable of multifunctional monitoring, they may provide more comprehensive monitoring data and reduce the cost and complexity of using multiple separate monitoring devices.
3. Multimodal signal sensing. Electronic skin devices have demonstrated potential for monitoring multiple types of signals, including biological, chemical, and physical sensing, which are crucial for comprehensive human health monitoring. The next step in the development of self-powered electronic skin based on TENG is to integrate these multiple modalities, taking advantage of advancements in neuroscience, the understanding new algorithms, and intelligent devices. This integration will facilitate the perception of multimodal signals and contribute to the development of advanced intelligent electronic skin systems, promoting the adoption of self-powered electronic skin based on TENG in wearable electronic products, intelligent robots, and prosthetic applications.
4. Neural interfaces. Neural interfaces have a wide range of application areas, including brain–computer interfaces, brain–robot interfaces, brain–computer interfaces, and so on. High-performance electronic skin based on TENG can enhance human–machine

interactions. By attaching electronic skin with various sensing functions to robots or intelligent prosthesis, external signals from the surrounding world can be sensed, creating a more immersive human–machine interaction experience. In the age of big data, real-time information and data can be wirelessly transmitted to users' mobile devices or computers for processing and analysis, enabling users to monitor their health and surrounding environment in real time. In the coming years, neural interfaces are expected to play an increasingly important role in computer–human interaction as science and technology advance.

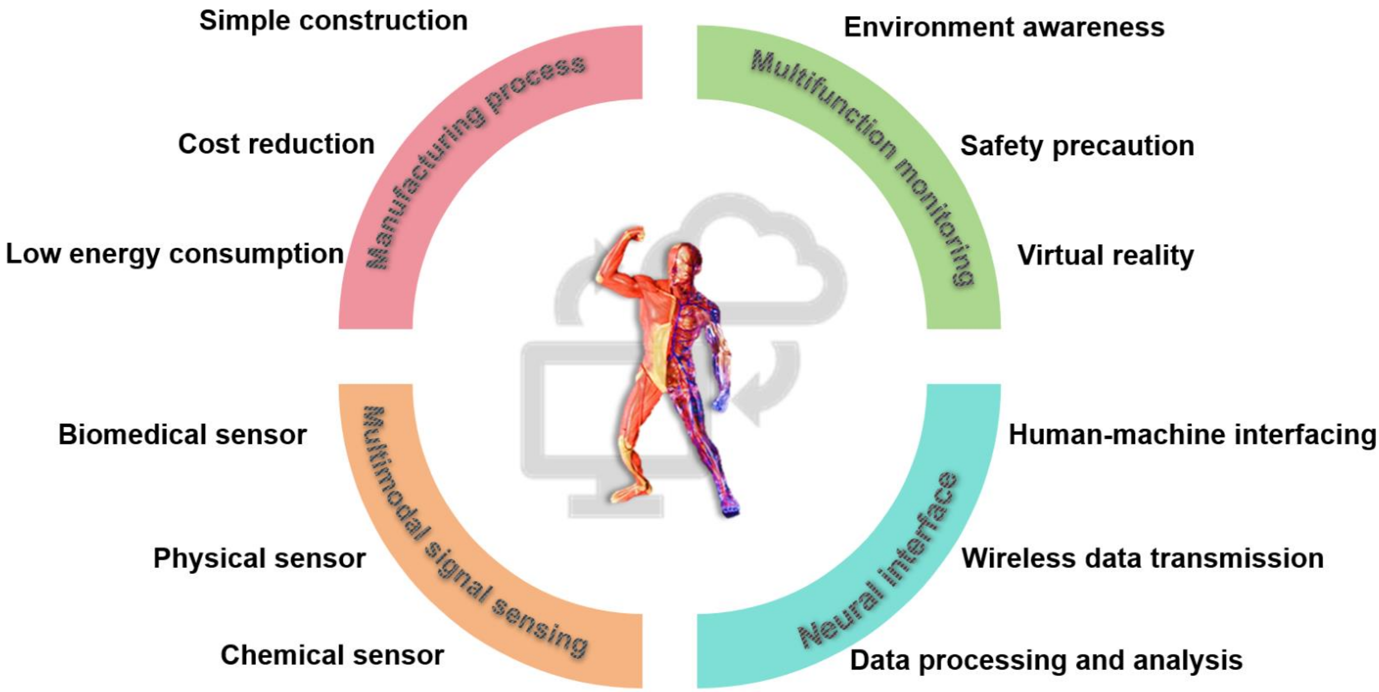

Figure 9. Perspective of self-powered electric skin based on TENG.

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