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REVIEW

Recent advances in stretchable triboelectric nanogenerators for use in wearable bioelectronic devices

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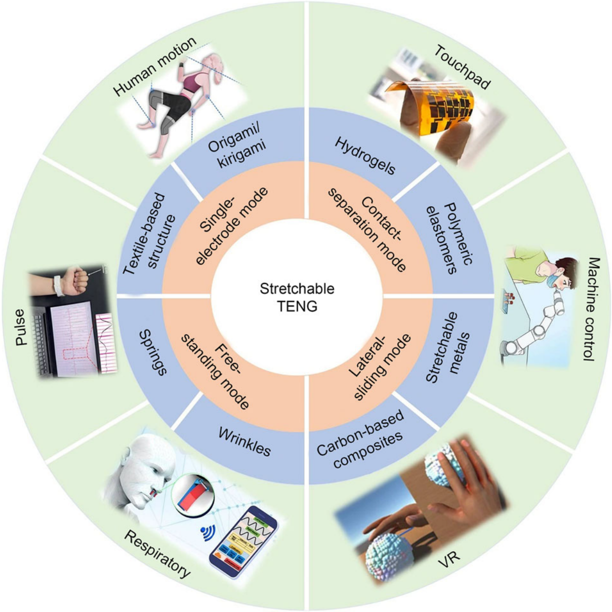
Abstract

Wearable bioelectronic devices have the capacity for real-time human health monitoring, the provision of tailored services, and natural interaction with smart devices. However, these wearable bioelectronic devices rely on conventional rigid batteries that are frequently charged or replaced and are incompatible with the skin, leading to a discontinuity in complex therapeutic tasks related to human health monitoring and human–machine interaction. Stretchable triboelectric nanogenerator (TENG) is a high-efficiency energy harvesting technology that converts mechanical into electrical energy, effectively powering wearable bioelectronic devices. This study comprehensively overviews recent advances in stretchable TENG for use in wearable bioelectronic devices. The working mechanism of stretchable TENG is initially explained. A comprehensive discussion presents the approaches for fabricating stretchable TENG, including the design of stretchable structures and the selection of stretchable materials. Furthermore, applications of wearable bioelectronic devices based on stretchable TENG in human health monitoring (body movements, pulse, and respiration) and human–machine interaction (touch panels, machine control, and virtual reality) are introduced. Ultimately, the challenges and developmental trends regarding wearable bioelectronic devices based on stretchable TENG are elaborated.

Graphic abstract



Keywords Stretchable · Triboelectric nanogenerators · Structure · Human health monitoring · Human–machine interaction

Introduction

Wearable bioelectronic devices, including electronic skins, temperature sensors, strain sensors, and humidity sensors, are experiencing rapid development in the field of medical technology and human–machine interaction [1–5]. Wearable bioelectronic devices offer users the capability of real-time human health monitoring and natural interaction with smart devices. Successful applications of wearable bioelectronic devices include monitoring heart rate, respiration, body temperature, human motion, and human–machine interaction [6–10]. However, as wearable devices advance, an increasing number of challenges arise. These pertain to the application of wearable systems in continuous human health monitoring, reliable signal detection and analysis, and providing a comfortable and natural user experience [11–13]. To achieve these objectives, the use of wearable bioelectronic devices necessitates the integration of more advanced sensors and actuators into a comprehensive system. Furthermore, a consistent power source is imperative to sustain the proper functioning of all components within the system [14–16]. Most wearable bioelectronic products rely on rigid lithium-ion batteries without viable self-charging technologies. These batteries must be frequently recharged or replaced, leading to the complex, cumbersome, and environmentally unfriendly usage of wearable systems [17–19]. Therefore, the development of efficient stretchable new energy sources presents a challenge.

The development of new energy sources primarily includes solar energy, wind energy, thermoelectricity, piezoelectricity, and triboelectricity [20–24]. Among these, the triboelectric nanogenerator (TENG) stands out as a nanoscale energy harvesting technology based on the principles of friction and electrostatic induction [25–27]. It effectively converts mechanical into electrical energy, facilitating energy capture and storage. This novel and efficient energy collection method holds significant relevance in the field of wearable bioelectronic devices. Wang et al. [28] developed a self-powered woven TENG that not only holds the potential for large-scale industrial production but also guarantees comfort during wear. This innovative device can be used for motion monitoring and energy harvesting. However, the stretchability of this woven TENG is limited, which could impede the rapid progress of wearable bioelectronic devices. Stretchable TENG offers higher flexibility and adaptability than self-powering technologies such as solar, thermoelectric, and piezoelectric systems. Stretchable TENG can be applied across various motion scenarios and forms [29–32]. In addition, its compact size and efficient energy conversion make it highly promising for a broader scope of applications in wearable bioelectronic devices. Leng et al. [33] have ingeniously employed protein-based biopolymer hydrogels to create stretchable TENG-based artificial skin. This engineered skin can be stretched up to 400%, allowing for the prolonged measurement of human electrophysiological signals and sensing. Building upon this biopolymer-based artificial skin, they have further developed intelligent robot control systems and Bluetooth-enabled mobile control systems, showcasing significant prospects in developing next-generation human–machine interfaces. To further enhance the stretchability of TENG, Cai et al. [34] employed polydimethylsiloxane (PDMS)/MXene conductive composite materials to create a highly stretchable and shape-adaptable TENG-based electronic skin. This electronic skin can be stretched up to 760%, maintaining excellent adhesion even on uneven human skin surfaces. Moreover, it retains the original triboelectric performance even after repeated damage. Such advancements hold immense potential for wearable bioelectronic devices. Consequently, developing stretchable TENG for wearable bioelectronic devices is highly imperative.

In this study, the discussion focuses on the latest advancements in stretchable TENG for wearable bioelectronic devices. As shown in Fig. 1, the review first explains the four operational mechanisms of stretchable TENG. Subsequently, various stretchable designs, including origami, textiles, springs, and wrinkles, are introduced, along with an in-depth description of stretchable materials such as hydrogels, polymeric elastomers, stretchable metals, and carbon-based composites. Moreover, this study discusses the applications of wearable bioelectronic devices based on stretchable TENG in human health monitoring, including body movements, pulse, respiration, and human–machine interaction, such as touch panels, machine control, and virtual reality (VR). Finally, this study outlines the challenges and offers corresponding solutions, along with predicting the developmental trends in wearable bioelectronic devices based on stretchable TENG.

Mechanisms of stretchable TENG

Stretchable TENG is a nanoscale power-generating device that harnesses the triboelectric effect to produce electricity. Stretchable TENG possesses a certain degree of stretchability, enabling it to generate electrical energy under deformed conditions. Its operation is based on the principles of frictional charge separation and electrostatic induction. By creating a surface charge difference through the relative motion of the two layers, stretchable TENG facilitates the flow of charges, leading to electrical power generation. There are four common operating modes for stretchable TENG:

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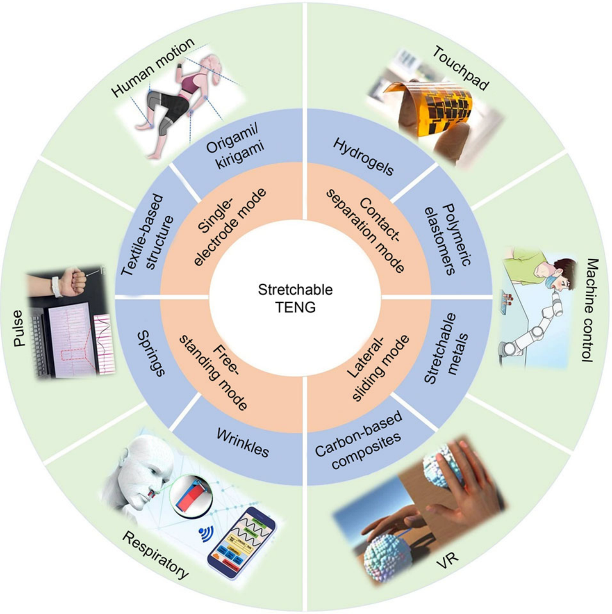

Fig. 1 Illustration of the demands of stretchable TENG for wearable bioelectronic devices. Image for "Human motion" was reproduced from Ref. [35], Copyright 2022, with permission from the American Chemical Society. Image for "Pulse" was reproduced from Ref. [36], Copyright 2023, with permission from the authors, licensed under CC BY 4.0. Image for "Respiratory" was reproduced from Ref. [37], Copyright 2022, with permission from the authors, licensed under CC BY-NC-ND. Image for "Touchpad" was reproduced from Ref. [38], Copyright 2020, with permission from Elsevier. Image for "Machine control" was reproduced from Ref. [39], Copyright 2022, with permission from Wiley-VCH GmbH. Image for "VR" was reproduced from Ref. [40], Copyright 2022, with permission from the authors, licensed under CC BY 4.0. TENG: triboelectric nanogenerator; VR: virtual reality

contact-separation, lateral-sliding, free-standing, and single-electrode modes [41–43].

One of the typical operating modes for stretchable TENG is the contact-separation mode. This mode primarily relies on the vertical position change between two materials with different electronegativities. In Fig. 2a, when polyimide (PI) comes into contact with copper (Cu) foil under pressure, opposite polarities of equivalent negative and positive charges are induced on the two surfaces. The PI surface acquires a negative charge, whereas the Cu foil surface develops a positive charge. Because of electrostatic induction, the conductive layer of Cu generates induced charges with opposite electrical characteristics, resulting in the creation of a potential difference. Induced charges transfer from the PI/Cu to the Cu electrode. When the separation distance between the PI and Cu layers reaches its maximum value, electrostatic equilibrium can be achieved, causing electron flow to cease [44]. The contact-separation mode is straightforward, generating a steady electrical energy output through repetitive external forces. It is typically employed to harness irregular, low-frequency mechanical movements such as vibrations and impacts.

The TENG structure in the lateral-sliding mode is similar to that of TENG in the contact-separation mode. However, unlike the contact-separation mode, the two friction layers operate in the lateral direction in the lateral-sliding mode. In Fig. 2b, when overlapping, there is nearly no potential difference between the bottom and top electrodes because the triboelectric charging region forms only on the surfaces of polytetrafluoroethylene (PTFE) and nylon polymers. As the nylon substrate slides outward, the contact area between the two polymers decreases gradually. As a result, opposing triboelectric charges are separated, and the electron flow moves from one electrode to the other. The electron flow continues as outward sliding until nylon and PTFE are completely separated. This leads to the accumulation of electrostatically induced positive and negative charges on the electrodes [45]. In the lateral-sliding mode, there is no need for space between the two friction layers, thus conserving space. This makes it easier to stack them in three-dimensional (3D) space. The lateral-sliding mode is well-suited for capturing high-frequency energy.

The abovementioned modes both require a connection between the two friction layers through a circuit. However, in some situations, linking these two layers may not be convenient, such as in the case of a moving human body. The free-standing TENG consists of two interconnected electrodes and an isolated charged layer. Figure 2c shows that a polyester fabric serves as the independent friction layer. Initially, the independent polyester fabric makes contact with the nylon electrode. Electrons transfer from nylon to the independent polyester fabric because polyester exhibits significantly stronger negative triboelectricity than nylon. As the independent polyester fabric slides toward the polyester electrode, electrons flow from the polyester to the nylon electrode. When the independent polyester fabric fully overlaps with the polyester electrode, electron flow ceases [46]. In this mode, the positions of the two electrodes remain unchanged, and there is no contact between the charged body and the two electrodes. Therefore, the frictional loss on the electrodes can be essentially ignored in the process of obtaining energy.

The single-electrode mode involves the removal of one electrode to simplify the TENG structure. In the single-electrode mode, there is only one electrode, and the other end of the circuit serves as the reference electrode for the electron source, which can be a large conductor or ground. In Fig. 2d, when the nylon film makes contact with the dielectric PDMS film surface, the PDMS film acquires negative triboelectric charges because of its stronger ability to capture negative charges, while the nylon film becomes positively charged. As the nylon film separates from the PDMS film, the potential difference increases, causing electrons to flow instantaneously from the silver nanowire (AgNW) electrode

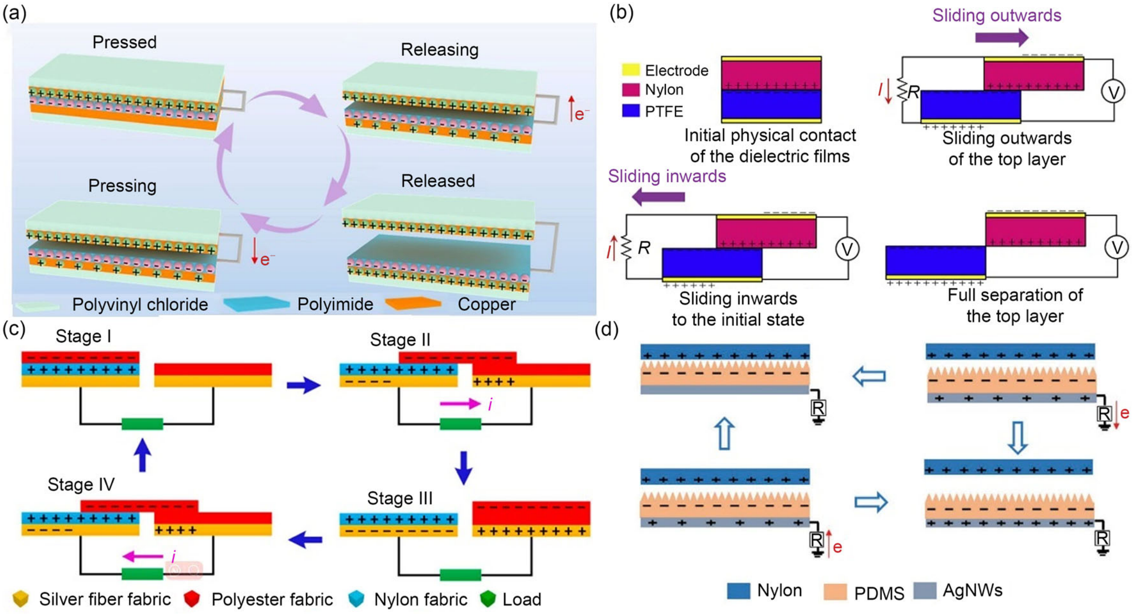

Fig. 2 Mechanism of TENG: **a** contact-separation mode (reproduced from Ref. [44], Copyright 2023, with permission from Elsevier); **b** lateral-sliding mode (reproduced from Ref. [45], Copyright 2019, with permission from Elsevier); **c** free-standing mode (reproduced from Ref. [46], Copyright 2014, with permission from the American Chemical Society); **d** single-electrode mode (reproduced from Ref. [47], Copyright 2020, with permission from Wiley-VCH GmbH). TENG: triboelectric nanogenerator

to the ground [47]. The primary advantage of the single-electrode mode lies in its simple structure. Under identical conditions, the single-electrode TENG performs at half the level of its counterpart with dual electrodes. Nevertheless, it is well-suited for mobile scenarios and is frequently employed in creating self-powered sensors.

Classification of stretchable TENG

Achieving stretchable TENG primarily involves two approaches: designing stretchable structures and fabricating stretchable materials. Designing a stretchable mechanism is akin to devising an array-structured TENG, which may comprise closely spaced metal electrodes and dielectric layers arranged in parallel [48] to increase the frictional area. Generally, the design of stretchable TENG structures can be categorized into origami, textile-based, spring-based, and wrinkle microstructures. Fabricating stretchable materials requires selecting materials with high flexibility and conductivity, such as polymers or elastic conductive materials [49]. In material selection, considerations must include stretchability and mechanical strength. Stretchable materials for TENG fabrication include hydrogels, polymeric elastomers, stretchable metals, and carbon-based conductive composites. The stretchability performance of stretchable TENG is demonstrated in Table 1 in the relative works.

Stretchable structure design

Origami/kirigami structure

The origami/kirigami structure technique transforms a flat plane into a complex 3D folding structure. By cutting, folding, and bending, it converts a nonstretchable two-dimensional (2D) into a 3D structure, allowing for out-of-plane deformations. This enables reversible material deformation, which features strong stretchability, foldability, and reconfigurability [68]. These exceptional properties have extensive applications in the field of wearable bioelectronic devices. Stretchable TENG based on the origami/kirigami structure amplifies a single triboelectric pair into a multilayered arrangement. This design features structural simplicity, compact size, low cost, and high electrical conversion efficiency [69, 70]. However, the manufacturing process requires specific materials and techniques, which may affect longevity and stability. Zhang et al. [71] developed a TENG using an origami tessellation structure. In Figs. 3a–3c, TENG is constructed using a folded paper structure comprising origami-tessellation-based quadrilateral prisms connected with friction pairs on the folded facets. The base of this folded paper structure is manually folded, providing multiple contact surfaces for installing friction pairs and enhancing stretchable TENG performance. This stretchable TENG presents an effective self-powering solution for intelligent transportation systems.

Table 1 Stretchability performance of stretchable TENG in relative works

Type	Materials/function	Stretchability	Reference
Origami/kirigami structures	Liquid metal/electrode	90%	[50]
Textile-based structures	Ag/electrode, PTFE/triboelectric materials	30%	[51]
	Cu/electrode	About 0.4%	[52]
	Waterproof flexible conductive fabric/electrode	60%	[53]
	Cu/electrode, PA6, and PVC/triboelectric materials	80%	[54]
Springs	Spiral steel wire/electrode	50%	[55]
	PTFE and nylon/triboelectric materials	80%	[56]
Wrinkles	PPFC/triboelectric materials	100%	[57]
	Conducting ink/electrode	100%	[58]
Hydrogels	Ionic hydrogel/triboelectric materials	>11,500%	[59]
	Hydrogel/electrode	400%	[60]
	PAM, HPMC, MXene hydrogels/electrode	2000%	[61]
	Ion-conducting hydrogel/electrode	About 850%	[62]
Polymeric elastomers	PDMS-PU$_x$-PA$_{1\text{-}x}$-Zn elastomers/electrode	1800%	[63]
	Electret elastomer/electrode	423%	[64]
	TPU, AgNWs/electrode	About 800%	[47]
Stretchable metals	Galinstan/electrode	About 300%	[65]
	Galinstan/electrode	70%	[66]
Carbon-based conductive composites	PVC gel, graphene/electrode	50%	[49]
	MXene/CNT	120%	[67]

TENG: triboelectric nanogenerator; PTFE: polytetrafluoroethylene; PA6: polyamide 6; PVC: polyvinyl chloride; PPFC: plasma-polymer-fluorocarbon; PAM: polyacrylamide; HPMC: hydroxypropyl methylcellulose; PDMS: polydimethylsiloxane; PU: polyurethane; PA: polyamide; TPU: thermoplastic polyurethane; AgNWs: silver nanowires; CNT: carbon nanotube

To improve the feasibility and stability of stretchable TENG, Pang et al. [72] introduced a waterbomb-inspired TENG using origami principles. In Figs. 3d–3h, the waterbomb-origami-inspired TENG exhibits unfolding and folding capabilities, enabled by its periodic origami design, which effectively increases the contact area of the friction layers. In addition, its electrical output performance remains stable after 57,600 contact-separation cycles, which can be used for self-powered traffic monitoring systems. The achieved perception accuracy surpasses 98%, promising to advance TENG technology in self-powered intelligent traffic systems. To enhance the extensibility of TENG, Li et al. [50] developed a stretchable self-powered electronic skin based on kirigami liquid metal paper electrodes. In Figs. 3i–3k, the process requires the deft implementation of the kirigami technique on EGaIn-based composite liquid metal paper electrodes, thus culminating in the fabrication of uniaxial kirigami structures. This architectural transformation is a self-powered electronic skin that can stretch up to 90%.

Textile-based structure

A textile-based structure is an intricate tapestry woven from intermingling fibers composed of yarn and silk, meticulously crafted through weaving and textile production [73]. The textile-based structure is primarily used as an electrode material in stretchable TENG [74, 75]. Mechanical movement engenders charge separation and accumulation, facilitating energy harvesting and power generation [76, 77]. Kwak et al. [51] introduced a stretchable TENG using a knitted fabric structure. In Figs. 4a–4d, this stretchable TENG adopts a dual-arc configuration comprising the upper and lower layers of knitted PTFE and Ag fabrics with an Ag electrode.

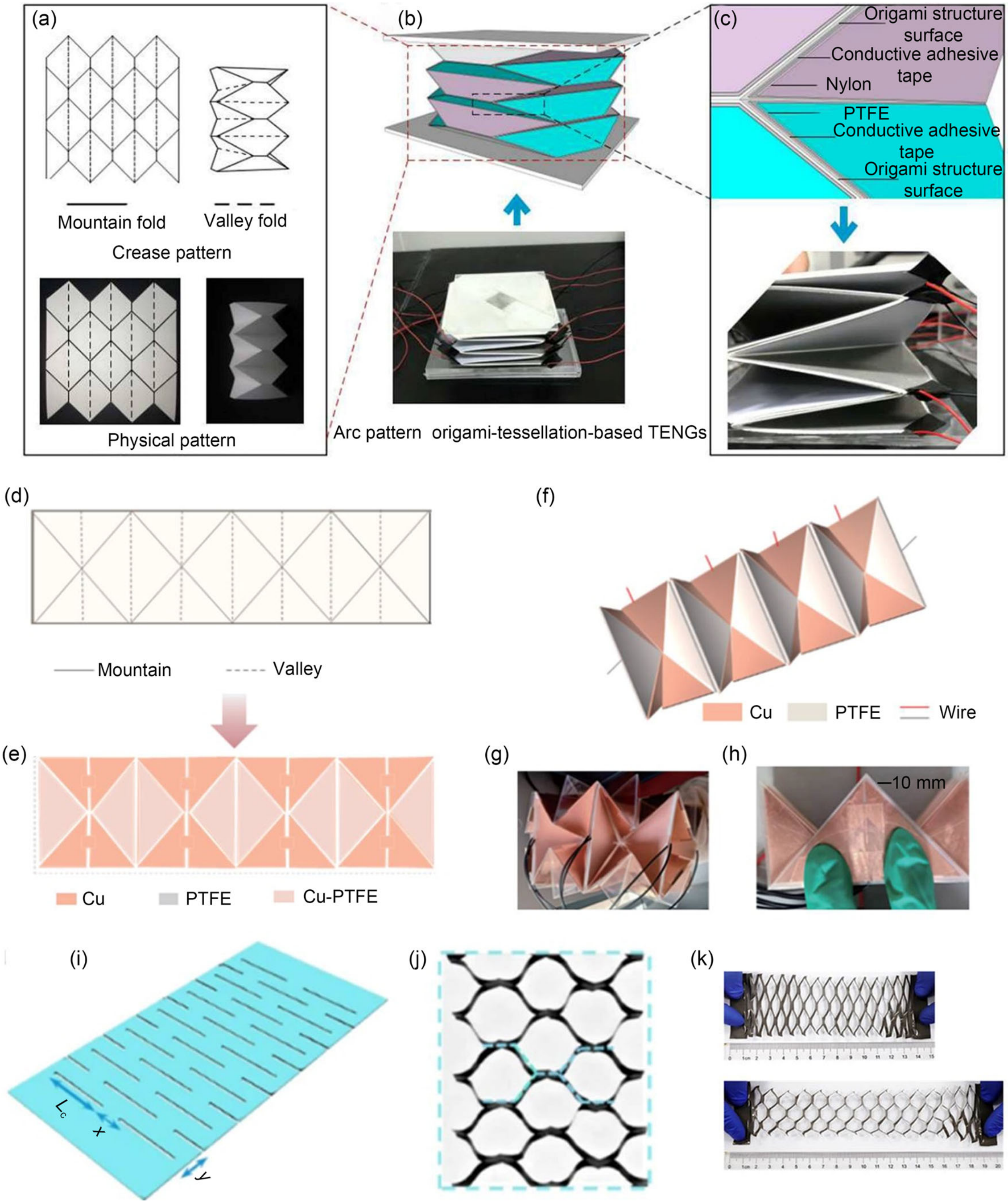

Fig. 3 **a**–**c** Design of origami-tessellation-based TENG (reproduced from Ref. [71], Copyright 2020, with permission from Elsevier). **d**–**h** Schematic of the waterbomb-origami-inspired TENG (reproduced from Ref. [72], Copyright 2022, with permission from Tsinghua University Press). **i**–**k** Schematic of the stretchable kirigami liquid metal paper electrode (reproduced from Ref. [50], Copyright 2022, with permission from the American Chemical Society). TENG: triboelectric nanogenerator

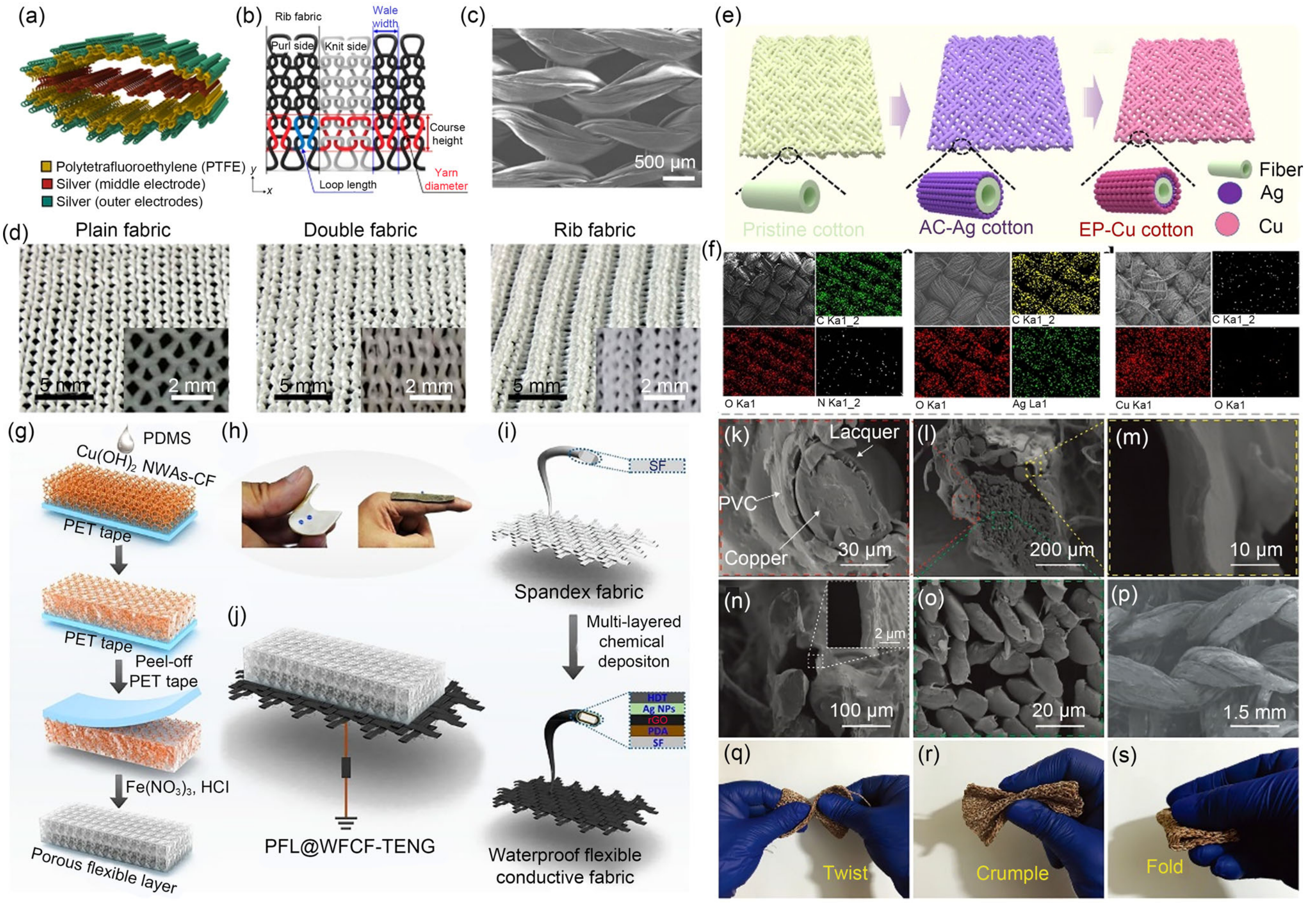

Fig. 4 **a**–**d** Stretchable TENG based on knitted fabric structures (reproduced from Ref. [51], Copyright 2017, with permission from the American Chemical Society). **e**, **f** Structure and characterization of EP-Cu cotton (reproduced from Ref. [52], Copyright 2023, with permission from The Royal Society of Chemistry). **g**–**j** Preparation process of a stretchable, single-electrode, textile-based TENG (reproduced from Ref. [53], Copyright 2021, with permission from Elsevier). **k**–**s** Characterization of stretchable and washable textile-based TENG (reproduced from Ref. [54], Copyright 2021, with permission from Wiley-VCH GmbH). TENG: triboelectric nanogenerator; EP-Cu: electroless Cu plating

The rib-knitting structure, characterized by superior stretchability (up to 30%), effectively amplifies the contact area, significantly enhancing the triboelectric power generation performance. To improve the recognition accuracy of textile-based TENG, Huang et al. [52] introduced a novel structural TENG through the PDMS encapsulation of electroless Cu plating (EP-Cu) on cotton, enabling multiple power generation mechanisms. In Figs. 4e and 4f, Ag is adsorbed onto the raw cotton to form Ag-adsorbed cotton (AC-Ag cotton). Subsequently, Cu is electroplated to AC-Ag cotton to create Cu-plated cotton (EP-Cu cotton). EP-Cu cotton serves as the electrode of TENG, whereas the encapsulation layer PDMS is the negative friction material of TENG. This device can distinguish eight distinct touch materials with an accuracy of 99.48% in an open environment.

To develop stretchable TENG with moisture and sweat resistance, Wang et al. [53] devised an innovative textile-based TENG comprising a 3D porous flexible layer and waterproof flexible fabric-based electrodes. In Figs. 4g–4j, establishing a biomimetic superwetting structure significantly hinders water film formation on the surface of TENG in high-humidity environments, enhancing the stability of the device. The device maintains high output performance even in an atmosphere of 80% humidity and 0.9% (mass fraction) NaCl water mist. To design a washable and stretchable TENG, Rezaei and Nikfarjam [54] produced a stretchable and wash-resistant textile-based TENG. Scanning electron microscopy images of this textile-based TENG are shown in Figs. 4k–4p, showcasing the loops formed through the rib-knitting needles and the intertwined threads. Figures 4q–4s illustrate that the textile-based TENG is subjected to the mechanical strain of twisting, wrinkling, and folding, underscoring the structural stability of this fabric-based TENG. This textile-based TENG can be stretched to 80% and is washable for up to 60 cycles.

Springs and wrinkles

The spring structure constitutes a mechanical arrangement imbued with elastic properties, typically crafted from flexible materials. It can undergo deformation under external force and subsequently return to its original form upon the removal of the force [78]. Incorporating spring structures into stretchable TENG requires a comprehensive assessment of factors such as material elasticity, mechanical characteristics, and energy conversion mechanisms [79]. Xie et al. [55] ingeniously opted for spring-like geometrically designed steel wires as electrodes and silicon rubber as the frictional electrification layer, crafting a fiber-shaped stretchable TENG. In Figs. 5a–5d, the fiber-shaped flexible and stretchable TENG based on spiral steel wires elegantly employs steel wires with a high Young's modulus. These wires are geometrically designed into spiral-shaped electrodes and are combined with an elastic matrix-organic silicone rubber. The fiber-shaped flexible TENG can be stretched up to 50% and exhibit high stability and tailorability. To improve the sensitivity to minor tensile strains, Ning et al. [56] devised a spring-structured optical fiber strain sensor based on a TENG. In Figs. 5e and 5f, this TENG leverages its spring structure, and even slight stretching leads to alterations in the contact state between the two frictional layers (PTFE and nylon), generating effective electrical signals. Consequently, it can respond to subtle tensile strains of <1%, which holds the potential for the preliminary diagnosis of respiratory system disorders.

A wrinkle is a configuration where the surface exhibits features such as ripples, folds, or creases. This type of structure generates a sequence of undulations on the material surface, resembling folded paper or wave-like patterns. In stretchable TENG, a wrinkled structure can augment the effective accumulation area on the material surface, thus enhancing friction efficiency and charge collection efficacy [80–84]. Cho et al. [57] fabricated a stretchable TENG based on a multilevel microscale–nanoscale wrinkled structure. In Fig. 5g, this wrinkled TENG is crafted using a composite target made of PTFE and carbon nanotubes (CNTs). This wrinkled TENG can be stretched up to 100%. It has the characteristics of environmental friendliness and a simple preparation process, which could be applied in raindrop energy harvesting and self-powered electronic skin. To achieve high-performance stretchable TENG, Wu et al. [58] introduced conductive ink electrodes featuring a wrinkled structure. In Figs. 5h and 5i, this wrinkled electrode is prepared by coating a prestretched very high bonding (VHB) tape surface with conductive ink and releasing the tension. This TENG exhibits stretchability, torsion capability, high power density, and robust mechanical performance. It can effectively achieve active motion monitoring and energy harvesting even on irregular surfaces.

Other structures

In addition to the aforementioned configurations, the electrode material or friction layer of TENG is designed as bulking structures (island bridges, serpentine, arc shape), cracks, assembling structures, and 3D porous structures [85–87]. Among them, bulking structures and cracks are appropriate for fabricating stretchable TENG. Wu et al. [88] employed a design incorporating an island bridge of liquid metal and silicone to fabricate a multimodal, stretchable TENG. This stretchable TENG exhibits extensibility, high conductivity, and excellent biocompatibility with the skin, allowing real-time monitoring of physiological signals such as pulses and human movements. Xiao et al. [81] used microcracks and folds in poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PEDOT:PSS) as electrodes and friction layers for stretchable TENG, achieving a self-powered tactile sensor. This sensor can stretch up to 100%, demonstrating remarkable pressure sensitivity, outstanding stability, and durability.

Stretchable materials

Hydrogel

Hydrogel is a gel material with high water content, typically composed of water and a 3D polymer network. Its softness and malleability make it suitable as a stretchable component for TENG [89, 90]. When a hydrogel undergoes mechanical deformation, the water and 3D polymer network within it move relatively, generating static electricity effects that result in charge separation and accumulation [91]. Guo et al. [59] employed an amphiphilic ionic network hydrogel as an ion conductor to develop a stretchable, transparent, and freeze-resistant TENG. In Fig. 6a, this TENG is fabricated by sandwiching the amphiphilic ionic network hydrogel between two layers of PDMS using the hydrogel as a collector. When applied to a multifunctional capacitive touch panel, TENG maintains its functionality even under high stretching conditions (1600%). It can be operated on complex surfaces, exhibiting exceptional input characteristics through activities such as writing and playing computer games. To enhance the conductivity of the hydrogel, Zhao et al. [60] harnessed medical conductive hydrogel as electrodes and silicone rubber as the frictional electrification layer, resulting in a novel stretchable TENG (Figs. 6b and 6c). When the medical conductive hydrogel is connected to a circuit, light-emitting diodes are illuminated, demonstrating

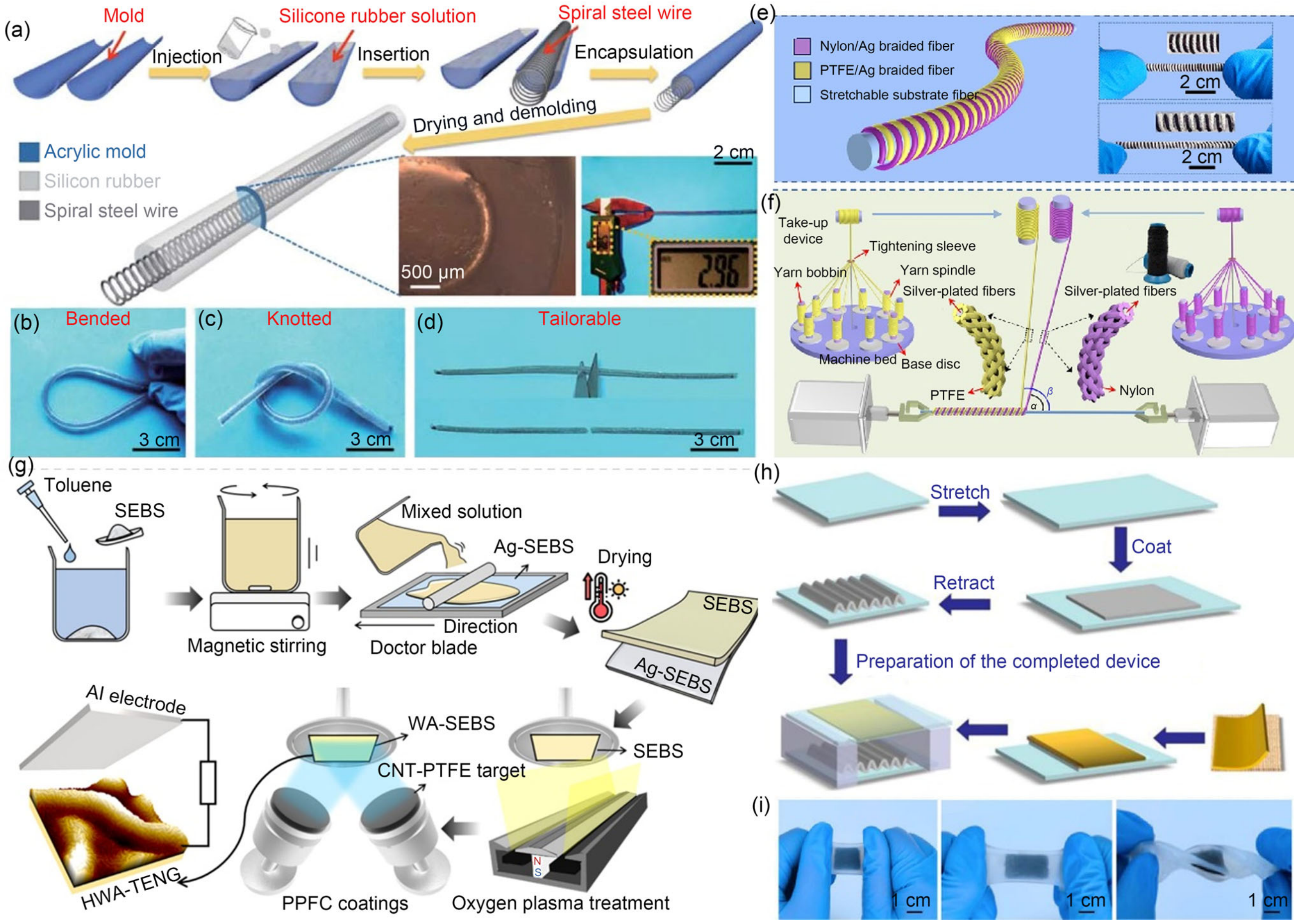

Fig. 5 **a**–**d** Schematic of stretchable TENG based on the spring structure (reproduced from Ref. [55], Copyright 2019, with permission from the authors, licensed under CC BY 4.0). **e**, **f** TENG-based spring-type fiber-optic strain sensors (reproduced from Ref. [56], Copyright 2022, with permission from the American Chemical Society). **g** Preparation process of hierarchical wrinkled TENG (reproduced from Ref. [57], Copyright 2022, with permission from the authors, licensed under CC BY 4.0). **h**, **i** Preparation process of conductive ink-based wrinkled TENG (reproduced from Ref. [58], Copyright 2022, with permission from Elsevier). TENG: triboelectric nanogenerator

the excellent conductivity of the medical conductive hydrogel.

To improve the stretchability of the hydrogel, Li et al. [61] fabricated a dual-network composite hydrogel comprising polyacrylamide, hydroxypropyl methylcellulose, and MXene nanosheets. This composite hydrogel is the conductive electrode for stretchable TENG (Figs. 6d and 6e). The composite hydrogel exhibits an extraordinary stretchability of 2260%. TENG is constructed by layering the composite hydrogel between two layers of the VHB friction material. The formidable stretchability of VHB, combined with the stretching properties of the hydrogel electrode, imparts the TENG structure with flexibility. This TENG also functions as a strain sensor capable of permanently distinguishing letters. To achieve transparency in the hydrogel, Liu et al. [62] employed a self-developed ionic hydrogel as the conductive layer to create a stretchable transparent TENG. In Figs. 6f and 6g, this stretchable conductive ionic hydrogel is synthesized using acrylamide, acrylic acid, choline chloride, N,N'-methylenebisacrylamide, gelatin, and $NaNO_3$ via a photoinitiated gelation method. TENG exhibits exceptional stretchability, reaching up to 850% while maintaining a remarkable transparency level of 90%. This TENG can be used to monitor electronic signals generated by bending, twisting, and folding fingers.

Polymeric elastomers

Polymeric elastomers are elastic materials made from polymer substances with remarkable stretchability and resilience, making them well suited for use as stretchable components in nanogenerators, collecting mechanical energy and generating charges. The common polymeric elastomers include elastic fibers and elastic gels [92–94]. Jiang et al. [63]

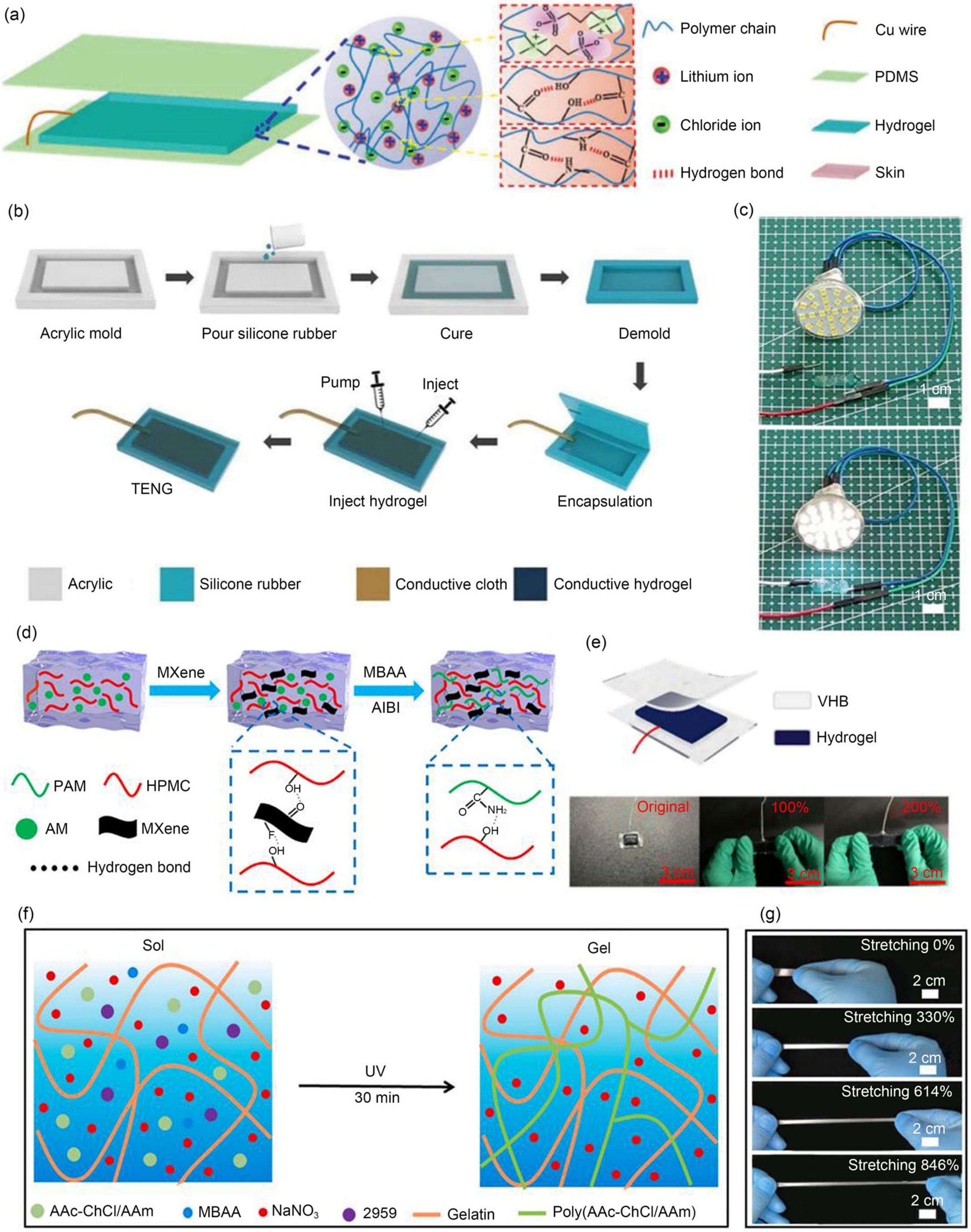

Fig. 6 **a** Structure diagram of the zwitterionic network hydrogel-based TENG (reproduced from Ref. [59], Copyright 2022, with permission from Wiley-VCH GmbH). **b**, **c** Schematic of the preparation of stretchable TENG based on medical conductive hydrogel (reproduced from Ref. [60], Copyright 2023, with permission from The Royal Society of Chemistry). **d**, **e** Structure diagram of stretchable TENG based on the composite conductive hydrogel (reproduced from Ref. [61], Copyright 2023, with permission from the American Chemical Society). **f**, **g** Schematic of ionic hydrogel-based stretchable TENG (reproduced from Ref. [62], Copyright 2022, with permission from Elsevier). TENG: triboelectric nanogenerator

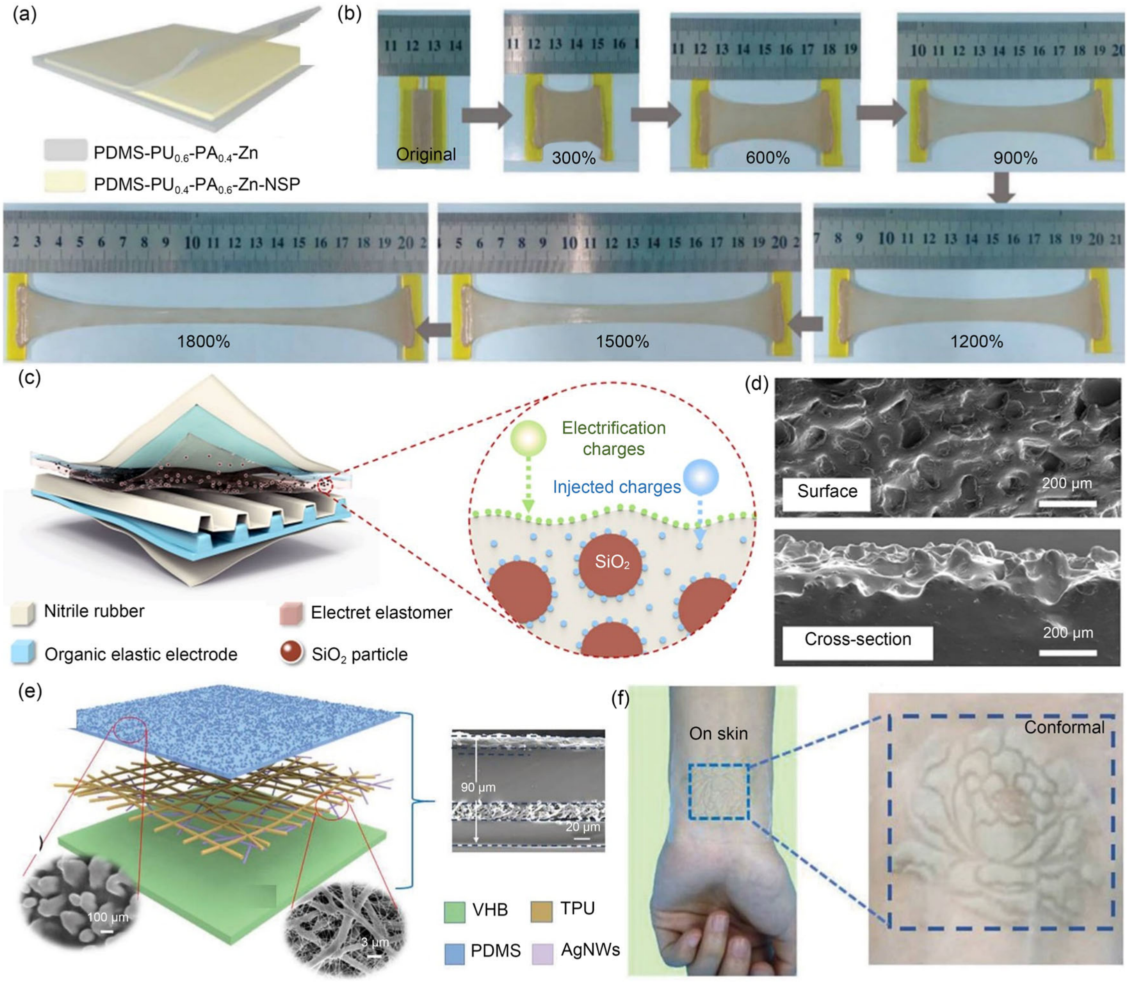

Fig. 7 **a**, **b** Schematic of the PDMS composite elastomer-based stretchable TENG (reproduced from Ref. [63], Copyright 2021, with permission from Wiley-VCH GmbH). **c**, **d** Schematic of the electret elastomer-based stretchable TENG (reproduced from Ref. [64], Copyright 2023, with permission from Elsevier). **e**, **f** Schematic of the TPU/AgNW composite-based stretchable TENG (reproduced from Ref. [47], Copyright 2020, with permission from Wiley-VCH GmbH). PDMS: polydimethylsiloxane; TENG: triboelectric nanogenerator; TPU: thermoplastic polyurethane; AgNW: silver nanowire

synthesized a composite elastomer of PDMS by introducing hydrogen bonds and dynamic metal–ligand coordination within PDMS chains. This composite elastomer exhibits exceptional stretchability (10,000%) and significant self-healing capabilities at room temperature (Figs. 7a and 7b). A PDMS composite elastomer is employed for the electrode and friction layer of a highly stretchable TENG. This TENG demonstrates excellent stretchability from 0% to 1800%. To enhance the power generation performance of a stretchable TENG, Liu et al. [64] proposed a stretchable dipole-based TENG. This TENG consists of an elastic dipole as the friction layer material and an organic hydrogel as the electrode. The elastic dipole is created by uniformly dispersing SiO_2 nanoparticles within an elastic substrate and thermally injecting static charges (Figs. 7c and 7d). Stretchable TENG possesses a significantly high charge density, making it suitable for powering wristwatches.

To achieve a high-stability stretchable TENG, Jiang et al. [47] employed thermoplastic polyurethane (TPU) and AgNWs to produce a stretchable composite electrode for a TENG. In Figs. 7e and 7f, this electrode is formed by evenly winding AgNWs and TPU nanofiber networks. This fabricated TENG can stretch up to 800%, exhibiting excellent biocompatibility, excellent stability, and self-powered sensing capabilities. It can be used as a tactile sensor array to detect human motion.

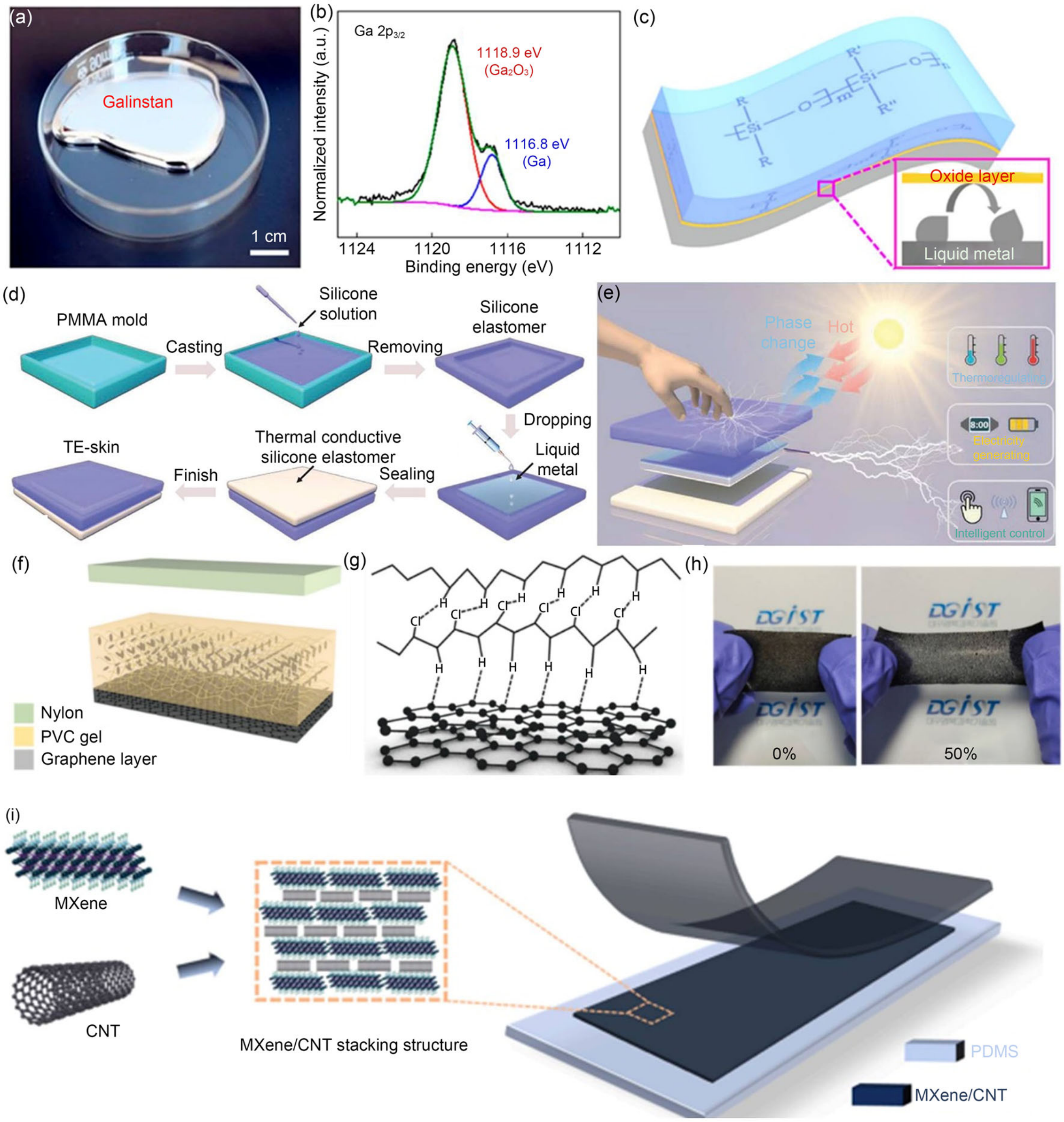

Fig. 8 **a**–**c** Characterization of the liquid–metal-based stretchable TENG (reproduced from Ref. [65], Copyright 2018, with permission from the American Chemical Society). **d**, **e** Preparation process of liquid–metal-based stretchable TENG and its intelligent control (reproduced from Ref. [66], Copyright 2021, with permission from Wiley-VCH GmbH). **f**–**h** Schematic of graphene-based stretchable TENG (reproduced from Ref. [49], Copyright 2022, with permission from Elsevier). **i** Schematic of the CNT composite-based stretchable TENG (reproduced from Ref. [67], Copyright 2023, with permission from Elsevier). TENG: triboelectric nanogenerato; CNT: carbon nanotube

Stretchable metal and carbon-based conductive composites

Stretchable metals are a class of metallic materials that possess elasticity and stretchability. Typically, they are engineered using methods such as alloying and microstructure manipulation to ensure that they undergo elastic deformation under stress while retaining their structural integrity. These materials are the electrode components for stretchable TENG [95–98]. Yang et al. [65] harnessed Galinstan as electrodes and silicon rubber as the triboelectric and encapsulation layers to fabricate a liquid–metal-based TENG (Figs. 8a–8c). The liquid metal functions as the electrode for TENG, exhibiting exceptional electrical conductivity and remarkable stretchability (300%). The liquid–metal-based TENG demonstrates the capacity to acquire mechanical energy from human movements such as walking, arm swinging, and hand clapping. Xiang et al. [66] introduced an innovative temperature-regulating electronic skin based on liquid metal. The TENG-based electronic skin is made of liquid metal as the electrode and silicone elastomer as the friction layer. This creation applies to human temperature modulation and human–machine interaction (Figs. 8d and 8e).

Carbon-based conductive composites combine carbon nanomaterials, such as CNTs and graphene, with polymers and elastomers. Carbon nanomaterials exhibit commendable conductivity, enabling the composite materials to retain electrical conduction during mechanical deformations. This attribute renders carbon-based conductive composites suitable for application as conductive elements within stretchable TENG, upholding charge conduction and separation during mechanical deformations [99, 100]. Kim et al. [49] innovatively used graphene electrodes in conjunction with polyvinyl chloride (PVC) gel to engineer a stretchable and biocompatible TENG (Figs. 8f–8h). This stretchable TENG remarkably maintains a consistent electrical output even at a maximum extension of 50%, effectively converting touch and pressure into a stable electric signal, which is suitable for self-powered electronic skin. To improve the stretchability of TENG, Wang et al. [67] pioneered the use of CNT/MXene as an electrode material and PDMS/MXene as a friction layer to fabricate a stretchable TENG (Fig. 8i). This stretchable TENG exhibits an impressive elongation capacity of up to 120%. Within the realm of low moduli, the MXene/CNT electrodes of this TENG display exceptional strain sensitivity, with a measurement factor as high as 238.8. This innovation holds great promise for wearable devices and intelligent robotics.

Stretchable TENG for wearable bioelectronic devices

Stretchable TENG plays a pivotal role in the field of wearable bioelectronic devices for providing a sustainable energy source [101, 102]. Within the domain of wearable bioelectronic devices, stretchable TENG enables the monitoring of human health parameters such as body sweat, heart rate, pulse, respiration, body temperature, muscle function restoration, body motion, hearing aid, neuromodulation, sleep, and blood pressure [103–106]. Zhao et al. [107] used stretchable conductive fiber to prepare TENG as a self-powered wearable biosensor for real-time sweat analysis. Yang et al. [108] developed a self-healing multifunctional stretchable TENG using hydrogels. TENG can be fitted to different human joints to self-monitor personal health information. In addition, human motion monitoring, pulse monitoring, and respiratory monitoring are detailed using stretchable TENG. Furthermore, they facilitate the realization of human–machine interaction encompassing touch panels, machine control, and VR.

Human health monitoring

Human motion

Monitoring human physical activities holds profound significance in facilitating individual health management. This practice extends its influence on diverse domains, including health promotion, optimizing exercise methods, medical rehabilitation, and scientific investigations. By seamlessly incorporating stretchable TENG into elastic bands, the mechanical energy generated during human movements and activities can be harnessed to power sensors, tracking data such as step counts for human health monitoring [109]. Li et al. [44] employed PI to fabricate a self-healing and stretchable TENG for human health monitoring. In Figs. 9a–9c, this stretchable TENG employs liquid metal as the conductive medium and a self-healing PI elastomer as the protective layer. This ingenious invention is a self-powered sensor for finger and wrist joint movements, efficiently detecting various human motions. Luo et al. [110] presented an innovative TENG based on a MXene/polyvinyl alcohol (PVA) hydrogel (MH-TENG). In Figs. 9d and 9e, this MH-TENG exhibits remarkable stability and sensitivity toward continuous kinetic fluctuations, particularly manifesting its efficacy in capturing movements of the wrist and elbow. This demonstration underscores its potential application in wearable motion tracking. Wang et al. [35] pioneered the creation of a flexible, stretchable, and highly transparent TENG based on an asymmetrical polyacrylamide/$BaTiO_3$ composite film. This TENG-based sensor displays remarkable sensitivity in detecting human motions such as finger, knee, and heel movements (Figs. 9f–9h).

Pulse monitoring

Monitoring the human pulse not only provides insights into cardiac health but also holds profound significance in the fields of medicine, health management, and scientific research, improving overall health and quality of life. By affixing a stretchable TENG onto the wrist, subtle mechanical fluctuations in the pulse can be carefully tracked [111, 112]. Zhi et al. [113] engineered a self-powered, biocompatible, and antibacterial fully textile-based TENG for tactile sensing. In Figs. 10a–10d, this self-powered tactile sensor employs a frictional pair of MXene doped PVDF (P/M) and Ag@nylon. When affixed to a volunteer's pulse points, the full textile-based TENG can be employed to discern pulse waves in the brachial and radial arteries. Wang et al. [114] presented a TENG-based self-powered tactile sensor showcasing a multitiered PDMS friction layer and PDMS/EGaIn composite electrodes. This sensor has an ultralow pressure detection limit of 0.23 Pa. In Figs. 10e and 10f, the self-powered tactile sensor is directly affixed to the human wrist, enabling the

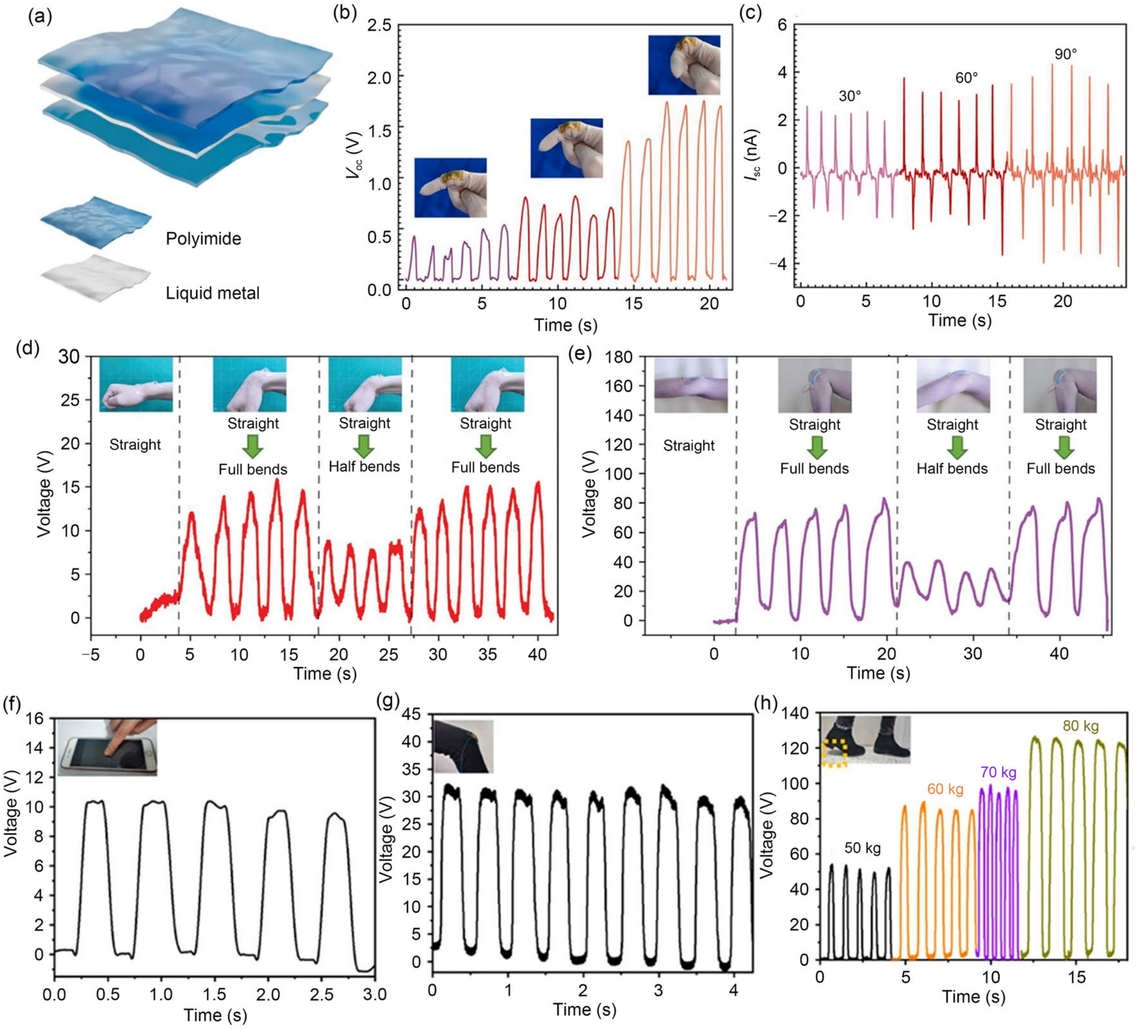

Fig. 9 Stretchable TENG for human motion: **a**–**c** stretchable TENG for finger motion monitoring (reproduced from Ref. [44], Copyright 2023, with permission from Elsevier); **d**, **e** MXene/PVA hydrogel-based stretchable TENG for wrist and elbow motion monitoring (reproduced from Ref. [110], Copyright 2021, with permission from Wiley-VCH GmbH); **f**–**h** asymmetric piezoelectric $BaTiO_3$ composite hydrogel-based stretchable TENG for finger, knee, and heel monitoring (reproduced from Ref. [35], Copyright 2022, with permission from the American Chemical Society). TENG: triboelectric nanogenerator; PVA: polyvinyl alcohol

monitoring of distinct pulse characteristic peaks. Sun et al. [36] developed a TENG-based self-powered multifunctional wristband. In Figs. 10g–10i, this versatile wristband demonstrates acute sensitivity in detecting physiological signals of pulse waves while exhibiting robust resilience against interference during motion.

Respiratory monitoring

Breathing is a fundamental process that upholds life, through which organisms access oxygen to support cellular metabolism and expel produced waste products. Using stretchable TENG for monitoring human respiration not only facilitates an enhanced comprehension of breathing patterns and depths for breathing exercises and regulation but also proves advantageous in assessing patients' rehabilitation progress and respiratory function [115]. Zou et al. [116] presented a stretchable self-powered respiratory sensor that simulates the gills of a shark. Endowed with commendable flexibility, extensibility, and fatigue resistance, it concurrently exhibits graded electrical response characteristics to varying degrees of tensile strain. When employed for sensing human respiratory movements, it enables simultaneous detection of respiratory rate and depth (Figs. 11a and 11b). Li et al. [117] reported a stretchable self-powered sensor tailored for respiratory assessment that is adept at discerning respiratory rate, apnea, and ventilation dynamics (Figs. 11c–11f).

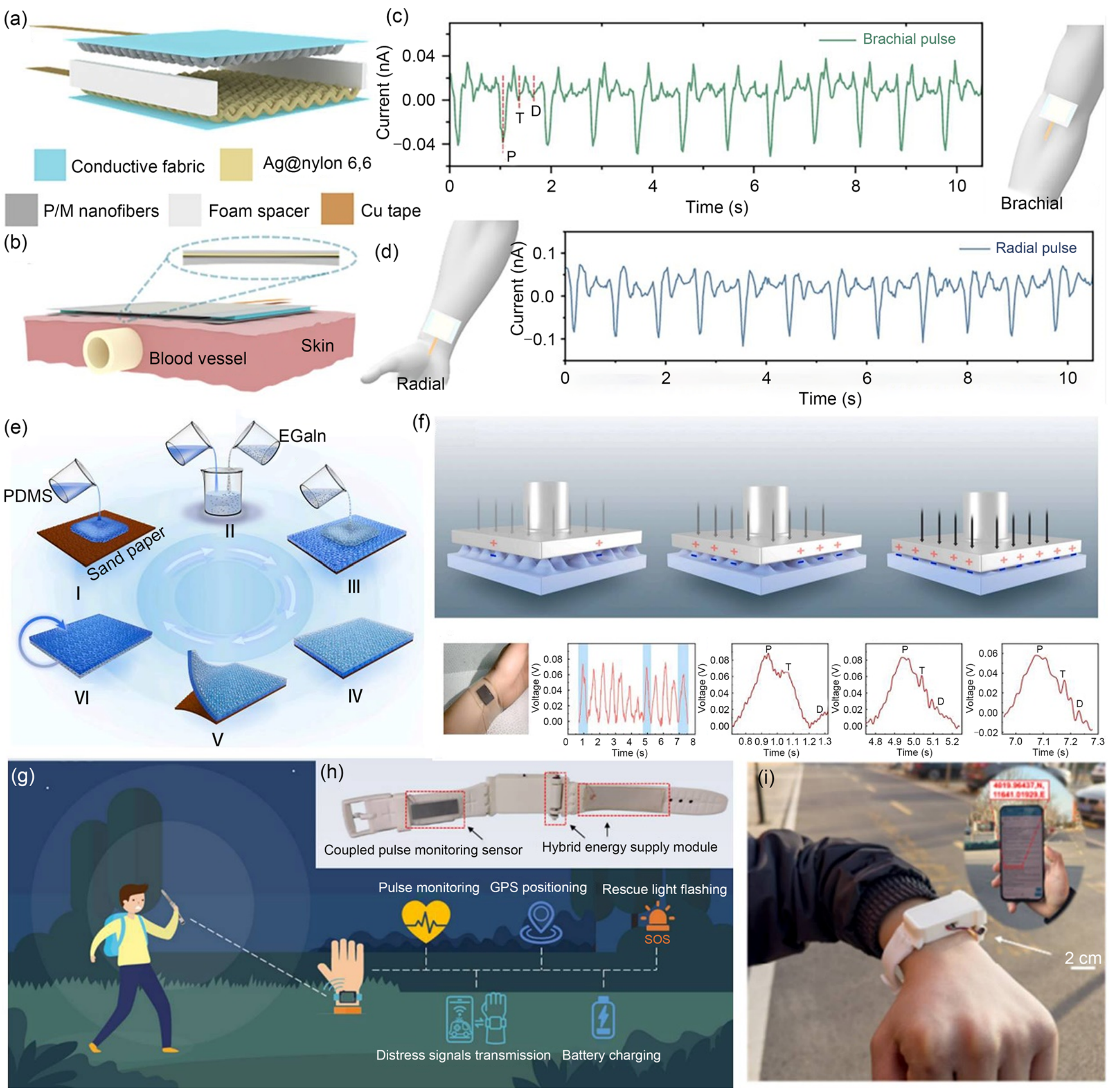

Fig. 10 Stretchable TENG for human pulse monitoring: **a**–**d** fully textile-based TENG (reproduced from Ref. [113], Copyright 2023, with permission from Elsevier); **e**, **f** TENG-based tactile sensors (reproduced from Ref. [114], Copyright 2021, with permission from Elsevier); **g**–**i** self-powered multifunctional wristband (reproduced from Ref. [36], Copyright 2023, with permission from the authors, licensed under CC BY 4.0). TENG: triboelectric nanogenerator

Building upon this advancement, a multifunctional wearable respiratory monitoring system has been devised that is proficient in effectively tracking pivotal respiratory metrics such as breaths per minute and apnea occurrences and counts. This exemplifies its potential in personalized healthcare and human health monitoring. Li et al. [37] pioneered an intelligent respiratory monitoring sensor system capable of concurrently detecting an array of parameters related to human respiration (Fig. 11g). This system enables the wireless transmission of respiratory signals, real-time display, information extraction, and health status diagnosis through signal processing, wireless transmission modules, and an integrated user terminal system endowed with data calibration and analytical capabilities. Ning et al. [56] ingeniously engineered a spiral fiber strain sensor capable of responding to minute tensile strains and proficient in perceiving contractions and relaxations of the chest and abdomen attributed to heartbeat and respiration (Figs. 11h–11j). Building upon this, a wearable intelligent spirometer was introduced for real-time and self-powered measurement of forced vital capacity (FVC), forced expiratory volume in one second (FEV1), and peak expiratory flow (PEF) to diagnose potential respiratory system ailments.

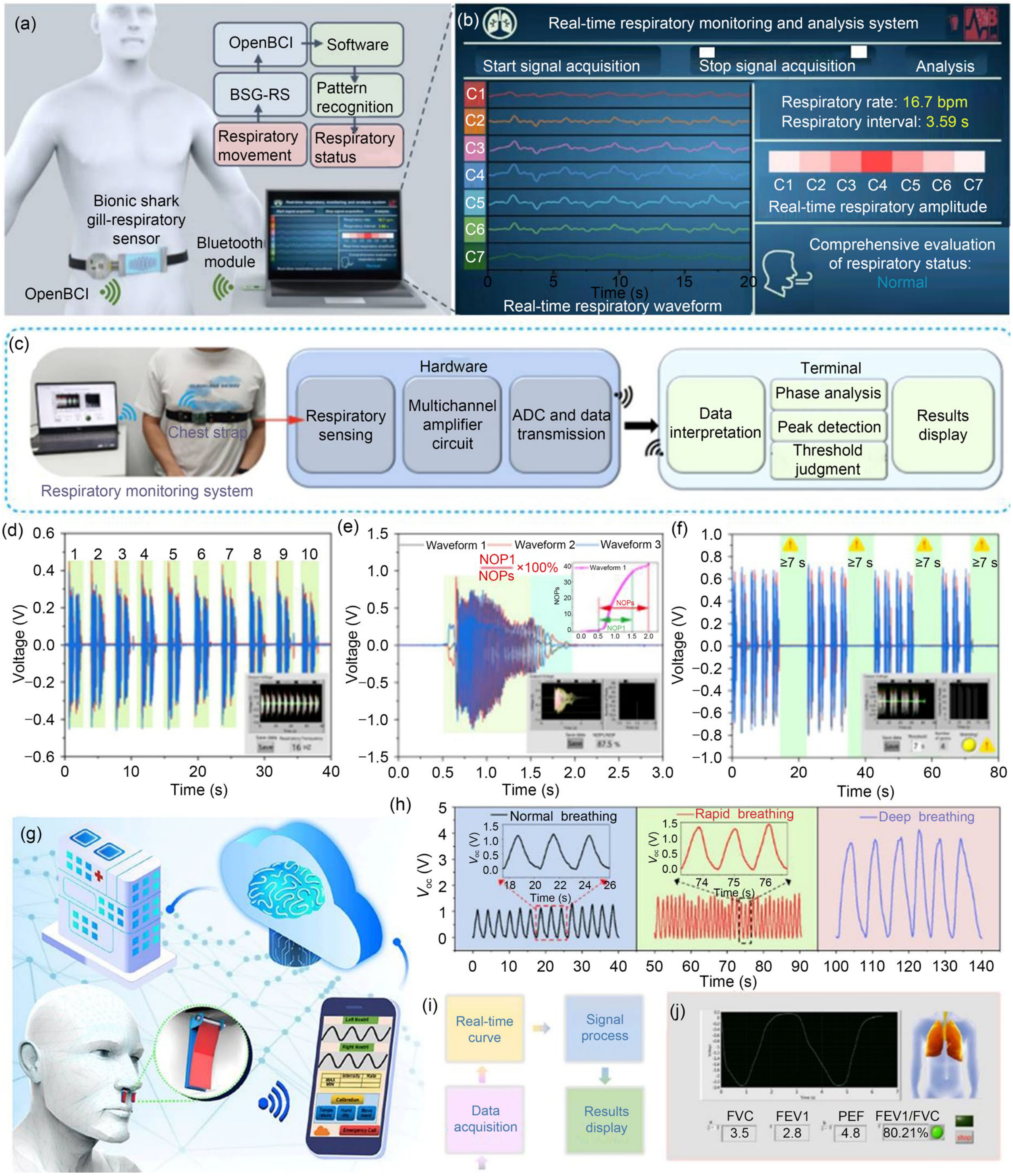

Fig. 11 Stretchable TENG for respiratory monitoring: **a**, **b** stretchable self-powered respiration sensor (reproduced from Ref. [116], Copyright 2022, with permission from the authors, licensed under CC BY-NC-ND); **c**–**f** stretchable thin-film multifunctional sensor (reproduced from Ref. [117], Copyright 2023, with permission from Tsinghua University Press); **g** smart multiparameter sensor system (reproduced from Ref. [37], Copyright 2022, with permission from the authors, licensed under CC BY-NC-ND); **h**–**j** TENG-based self-powered strain sensors (reproduced from Ref. [56], Copyright 2022, with permission from the American Chemical Society). TENG: triboelectric nanogenerator

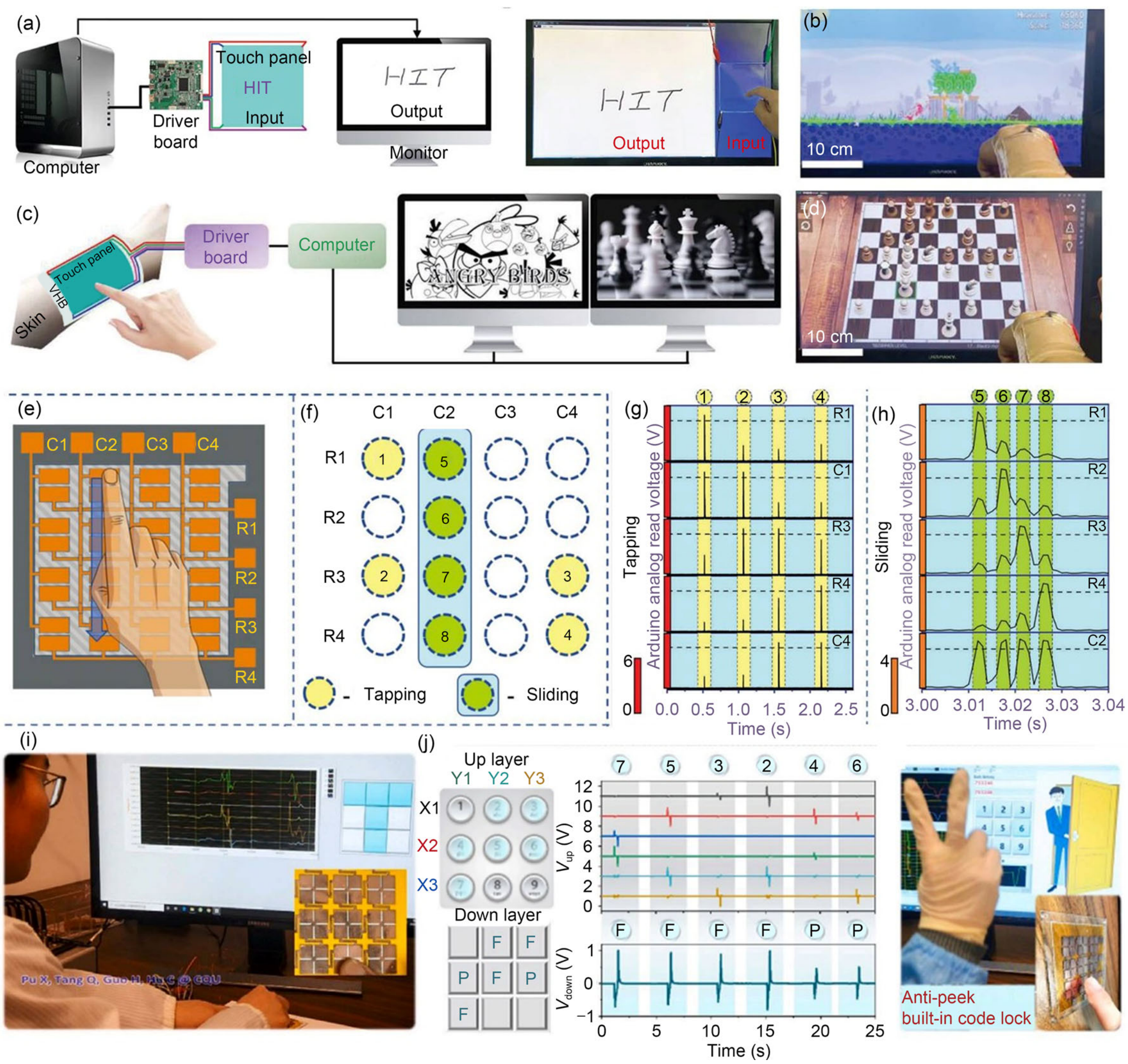

Fig. 12 **a**–**d** Super-stretchable TENG-based touch panel (reproduced from Ref. [59], Copyright 2022, with permission from Wiley-VCH GmbH). **e**–**h** Self-powered smart touch panel (reproduced from Ref. [119], Copyright 2023, with permission from Wiley-VCH GmbH). **i**, **j** Flexible triboelectric 3D touchpad (reproduced from Ref. [38], Copyright 2020, with permission from Elsevier). TENG: triboelectric nanogenerator

Human–machine interaction

Touchpad

A touchpad acts as an interface device, facilitating interaction between users and machines through tactile inputs. Conventional touchpads are typically fashioned from rigid materials such as glass or plastic. However, touchpads based on stretchable TENG introduce remarkable malleability and adaptability. This strain-responsive touchpad based on stretchable TENG provides energy and flexibility to devices without needing external power sources. This underscores its potential applications in mobile gadgets and wearable bioelectronic devices [118]. Guo et al. [59] pioneered the development of a multifunctional touchpad based on TENG. In Figs. 12a–12d, this touchpad not only serves as a human–machine interface but also exhibits rapid responsiveness, elevated resolution, and steadfast reliability. Demonstrating remarkable adaptability, it continues to perform diverse operations such as writing and gaming, even in varying conditions, including frigid temperatures and post-damage scenarios. Anithkumar et al. [119] ingeniously combined TENG and piezoelectric nanogenerators to craft a self-powered 4×4 matrix touchpad sensor. In Figs. 12e–12h, this innovation has applications in controlling computer interfaces or manipulating mouse pointers on touchscreen displays. This endeavor significantly paves the way for the evolution of multifunctional hybrid devices in the next generation of materials. Pu et al. [38] developed a self-powered,

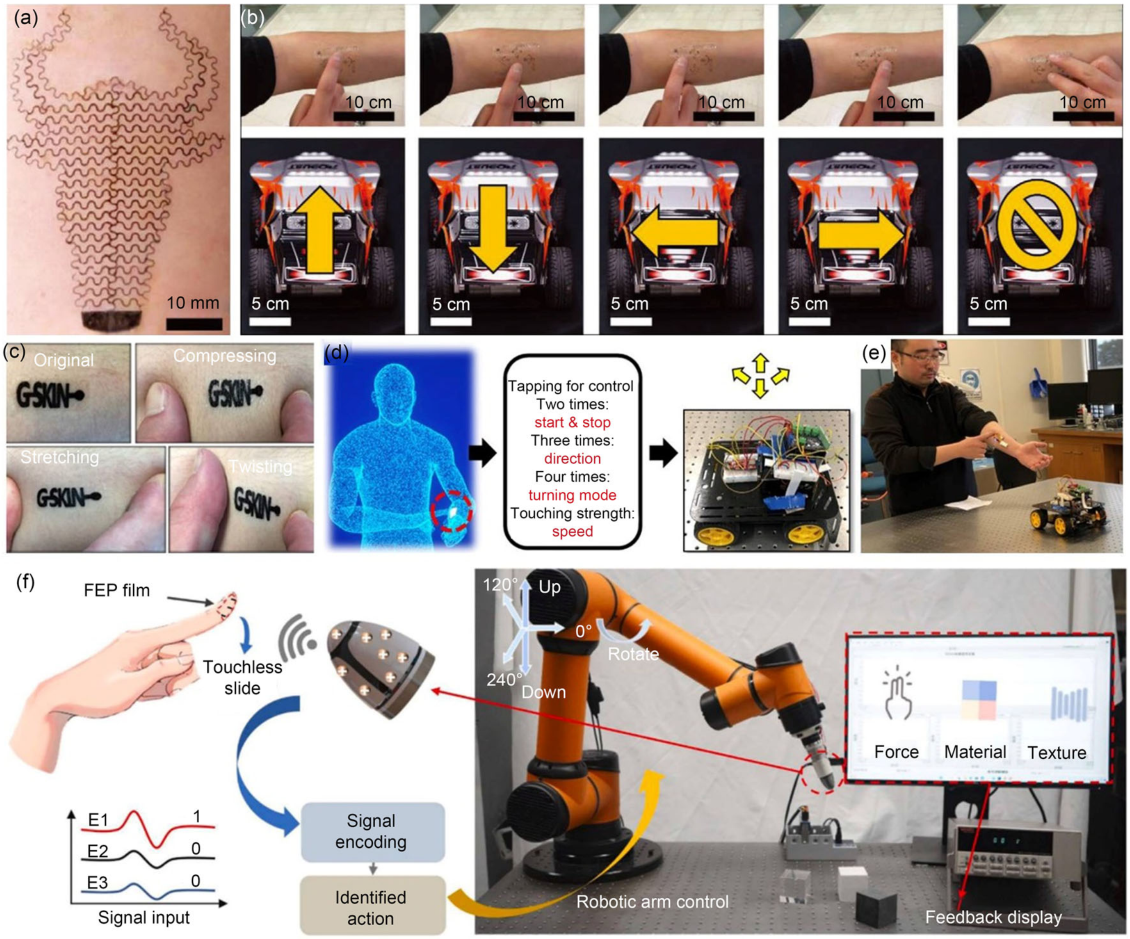

Fig. 13 **a**, **b** TENG-based tattoos for controlling electric vehicles (reproduced from Ref. [121], Copyright 2021, with permission from Wiley-VCH GmbH). **c**–**e** Tattoo-like TENG for wireless vehicle controllers (reproduced from Ref. [122], Copyright 2020, with permission from Elsevier). **f** A biomimetic electromechanical sensory finger (reproduced from Ref. [98], Copyright 2023, with permission from Elsevier). TENG: triboelectric nanogenerator

highly efficient, flexible 3D touchpad based on TENG. In Figs. 12i and 12j, this touchpad trajectory mapping is highlighted, dissecting positional and temporal cues within rows and columns to unveil the entire tracing process. The distinct design of this 3D touchpad opens expansive vistas for its application in domains ranging from motion monitoring and electronic skin to robotics and human–machine interaction.

Machine control

Machine control is the process of managing, guiding, and adjusting the operations, behaviors, and states of machines, equipment, or systems. Through machine control, the assurance of machine functioning according to predetermined parameters is realized, achieving the desired production, processing, or operational objectives. Integrating stretchable TENG into machinery, equipment, or systems for energy harvesting from mechanical deformation can revolutionize the field of machine control, enabling more intelligent and adaptive machines and devices to realize functions encompassing control, sensing, and power supply [120]. Wong et al. [121] introduced the ultrathin, flexible electronic tattoo TENG. This TENG exhibits exceptional mechanical properties while maintaining a thickness of mere tens of micrometers. In Figs. 13a and 13b, this electronic tattoo-like TENG finds its application in the realm of small electric vehicle remote controllers. By integrating Arduino programming and Bluetooth technology, it facilitates the wireless control of remote-controlled cars for maneuvering and turning. An et al. [122] employed vertically aligned gold nanowires to fabricate a tattoo-like stretchable TENG. This stretchable TENG can be seamlessly integrated with a flexible printed circuit board and is a remote-controlled light switch and wireless vehicle controller (Figs. 13c–13e). In pursuit of the combination of remote control and tactile interaction, Mu et al. [98] developed a biomimetic electromechanical sensory finger capable of energizing triboelectric electricity with visual

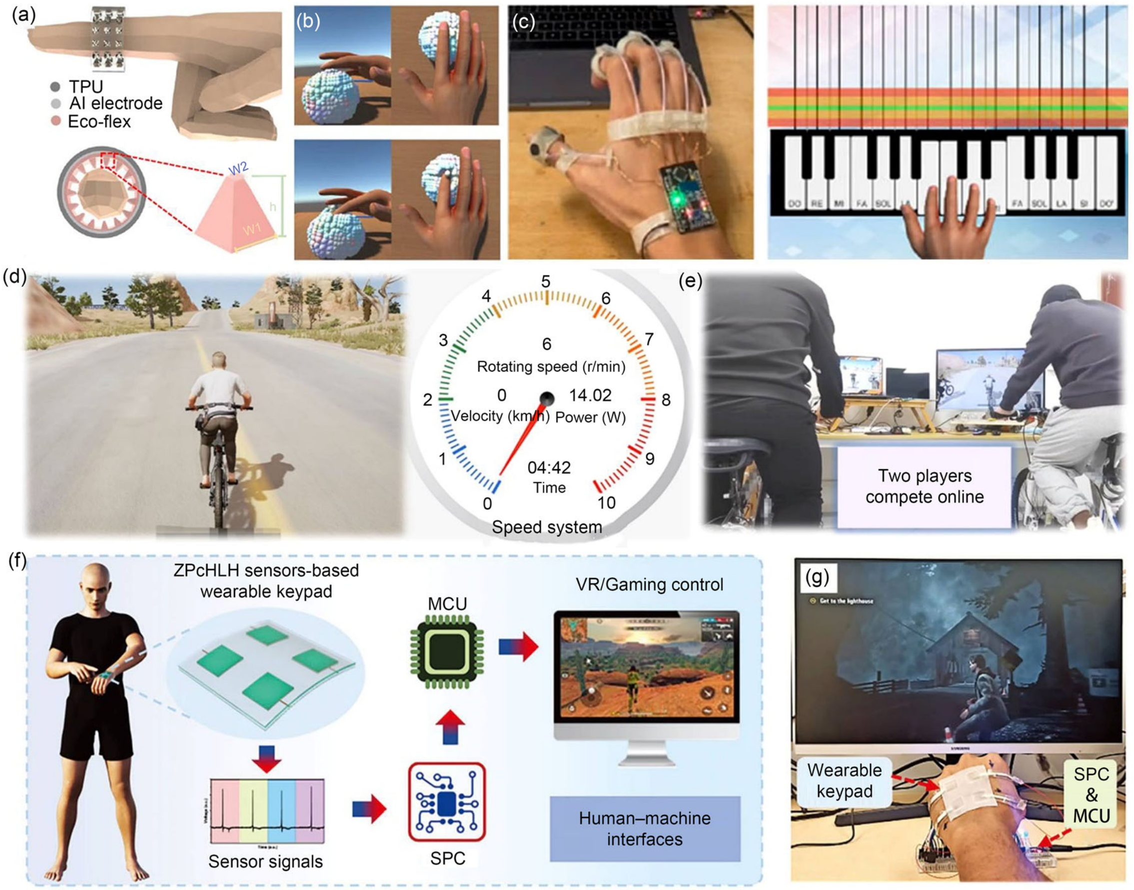

Fig. 14 **a**–**c** Haptic feedback rings (reproduced from Ref. [40], Copyright 2022, with permission from the authors, licensed under CC BY 4.0). **d**, **e** Multifunctional TENG for metauniverse motion interaction systems (reproduced from Ref. [126], Copyright 2023, with permission from Elsevier). **f**, **g** Highly stretchable hydrogel-based TENG for VR/gaming control (reproduced from [127], Copyright 2023, with permission from the authors, licensed under CC-BY-NC-ND). TENG: triboelectric nanogenerator; VR: virtual reality

and tactile sensations, designed for remote control and tactile perception (Fig. 13f). The convergence of noncontact and tactile sensing capabilities, as illustrated by the use of the FEP thin film, signifies the potential for noncontact manipulation of a robotic arm in 3D space.

Virtual reality (VR)

VR is an immersive experience brought to life through the intricate tapestry of computer technology. It transports users into a simulated environment, enveloping them in a realm that feels almost tangible, which is typically facilitated by specialized hardware such as head-mounted displays (VR headsets) and input devices such as controllers or gloves [123–125]. Within the realm of VR applications, users often engage using handheld controllers or similar mobile devices. These devices could seamlessly incorporate stretchable TENG, enabling the generation of electric energy during operation to recharge the internal batteries of devices, extending their operational endurance. Sun et al. [40] pioneered the development of a multifunctional ring adorned with a symphony of sensory and responsive capabilities. This innovative creation includes a TENG-based tactile sensor for the seamless perception of continuous bending, a flexible thermoelectric sensor adept at temperature detection, an eccentric rotary mass vibrator tailored for vibrational tactile feedback, and a nickel–chromium alloy metallic wire for delivering thermal tactile sensations. Through the artful fusion of sensing and feedback, an ingenious platform has been sculpted that boasts a capacity for spatial awareness, effectively engendering an immersive "metaverse" of interactions. In this wondrous realm, individuals participate in an immersive, face-to-face virtual social experience (Figs. 14a–14c). Zhu et al. [126] reported an extraordinary spatiotemporal interactive system based on TENG, materializing real-time interaction among individuals, devices, and networks. In Figs. 14d and 14e, this system is applicable to metaverse exercise interactions. During training sessions, participants not only have the capacity

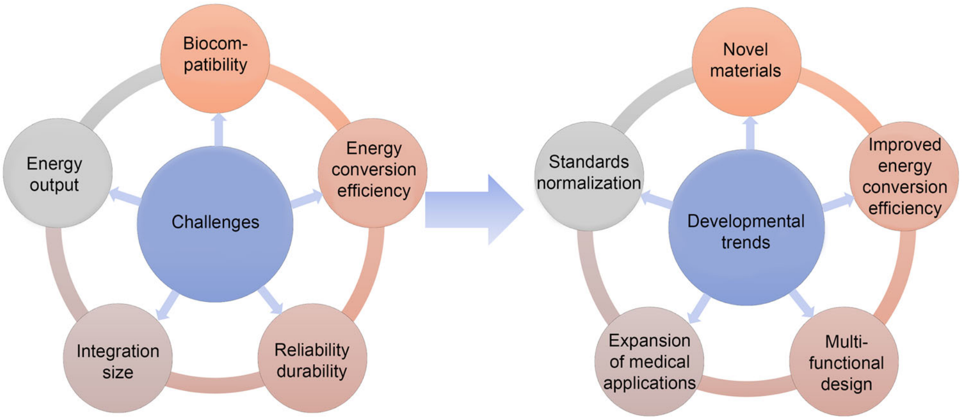

Fig. 15 Challenges and development trends faced by stretchable TENG for wearable bioelectronic devices. TENG: triboelectric nanogenerator

to monitor metrics such as cycling speed and power output but also exercise control over the gaming terminal, indulging in an immersive fitness experience. Ultimately, diverse trainees can engage in simultaneous online training sessions from distinct locations, with the training status of athletes mirrored through virtual avatars. Rahman et al. [127] presented a remarkably stretchable and durable TENG electrode. In Figs. 14f and 14g, this wearable TENG electrode can be employed within human–machine interaction systems, facilitating the manipulation of the computer game “Alan Wake.” This manifestation showcases the potential use of wearable TENG-based sensors in VR gaming, robotic control, and electronic epidermis.

Conclusions and outlook

This study provided a comprehensive overview of the latest advancements in stretchable TENG for wearable bioelectronic devices. Initially, the operational mechanism of stretchable TENG was elucidated. Subsequently, a comparative analysis and discourse on diverse stretchable structural designs and materials used for fabricating stretchable TENG was conducted. Furthermore, the applications of stretchable TENG in wearable bioelectronic devices, human health monitoring, and human–machine interaction were introduced.

Despite numerous proof-of-concept demonstrations in pertinent literature, actualizing the true potential of wearable bioelectronic devices based on stretchable TENG requires addressing the following intricate challenges (Fig. 15).

1. Biocompatibility: Because of direct contact with the human body, wearable bioelectronic devices must be compatible with human tissues to avoid allergic reactions or other adverse effects. Therefore, it is necessary to use materials with high biocompatibility.
2. Energy conversion efficiency: Charge transfer during the stretching process will result in decreased energy conversion efficiency of stretchable TENG. Therefore, there is a need for further research into the charge transfer properties of materials and optimization at the material and structural levels to enhance energy conversion efficiency. Potential strategies include refining electrode materials and optimizing charge transfer pathways.
3. Reliability and durability: Stretchable TENG must maintain stable performance after multiple stretches and deformations that can lead to material fatigue and degradation. Therefore, enhancing device reliability and durability can be achieved through careful material selection, structural optimization, and engineering design. Long-term cyclic testing and simulations should be conducted to assess the performance changes of the devices under repeated stretching.
4. Integration and size: Integrating stretchable TENG into practical wearable bioelectronic devices requires the consideration of device dimensions, shapes, and integration with other components. Therefore, to address integration challenges during the design phase, optimizing device dimensions and shapes to fit seamlessly with other components is crucial. Microfabrication techniques can be employed to manufacture small-sized devices, enhancing the overall integration performance.
5. Energy output: The energy output of stretchable TENG is limited and may struggle to meet the requirements of certain wearable devices requiring high energy. Combining other energy harvesting technologies, such as solar power and thermoelectric energy harvesting, can expand energy sources and enhance overall energy supply capacity. Depending on different application scenarios, choosing appropriate energy harvesting technologies is vital to meet specific energy demands.

In conclusion, while wearable bioelectronic devices based on stretchable TENG encounter challenges, the continuous advancement in materials science, nanotechnology, and electronic engineering holds the promise of gradually overcoming these hurdles. In the future, stretchable TENG may witness several developmental trends in the field of wearable bioelectronic devices. Some of these trends may include the following: (1) developing new materials with high stretchability, flexibility, and biocompatibility; (2) improving the energy conversion efficiency of stretchable TENG by optimizing the nanostructure, enhancing material properties, and using advanced electronic technology; (3) integrating stretchable TENG with other sensors, electronic components, and biomedical devices to enable multifunctional design; (4) applying stretchable TENG in various medical fields, including wearable medical devices and human health monitoring systems; (5) establishing more standards and specifications to ensure the interoperability of stretchable TENG across different devices as the field advances, enhancing their commercial application and market adoption (Fig. 15). These trends will facilitate the development of stretchable TENG in the field of wearable bioelectronic devices, enabling them to better fulfill the requirements of applications such as human health monitoring and human–machine interaction.

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Author contributions YLW was involved in writing the original draft; PCZ, YS, PL, and YCM contributed to writing, reviewing, and editing.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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

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