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Review

Design, manufacturing and applications of wearable triboelectric nanogenerators

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ABSTRACT

Amid the rapid flourishment of wearable electronics, the issue of power consumption has become increasingly prominent. With an extremely simple and universal configuration, triboelectric nanogenerators (TENGs) have emerged and performed huge advantages in converting low-frequency mechanical energy into electricity. Thus, TENGs in wearable forms are expected to capture the energy in human motions and in-situ drive wearable devices. Moreover, such a type of energy conversion allows us to excavate the rich information behind the output signals. In this review, we first introduce the basic design of TENGs suitable for wearable devices, including material selection, process modulation and optimization of the form factor. Then, we elaborate on three key roles that wearable TENGs play in the current era of smart Internet of Things (IOT), i.e., active sensors, actuators, and human-machine interfaces. Next, we summarize the progress of wearable TENG-powered systems at the performance level and process level. In the end, we make concrete prospects for this technology to move further into the actual market and approach the general public lives.

1. Introduction

With the continuous development of mobile terminals, portable/wearable electronic devices and daily health monitoring/management, the further follow-up of micro-processing level has received widespread attention. The reduction of feature size is not only for the pursuit of better performance, but also for the consideration of device power consumption. In the current bottleneck period, if we can replace the dependence on external energy with new energy supply mechanism, it will vastly propel the progress of the industry. Until Wang et al. invented the triboelectric nanogenerator (TENG) in 2012 [1], most of the energy harvesting methods on the market showed insufficient output power due primarily to the limited energy source or the inefficient conversion mechanism.

Table 1 summarizes the characteristics of various green generator technologies, where we can spot the advantages of TENG, especially in the field of wearable electronics. For example, solar cells use high-frequency radiation energy [2–4]; thermoelectric generators can absorb low-frequency heat [5,6]; yet both types of devices are obviously dependent on working conditions. Electromagnetic generators (EMGs) can efficiently utilize various forms of ambient mechanical energy [7,8], but the inherent material properties and bulky volume make it difficult to achieve flexible integration. Biofuel cells possess appealing biocompatibility [9,10] and piezoelectric generators (PENGs) hold outstanding sensitivity [11–14], whereas their efficiencies are not satisfactory. In contrast, TENGs have incorporated many superiorities such as wide selection of materials [15], simple configurations [16], and low cost [17]. Most importantly, TENGs can convert the low-frequency mechanical energy contained in the neglected body movement into real-time high voltage outputs [18].

Therefore, TENGs will build a bridge between people's daily routine and wearable/portable functional electronics. Since TENGs are based on the triboelectric effect between any two materials with different electronegativity (i.e., the ability to attract electrons) [1], the design wearable TENG should not only consider its output performance, but also think about building a more intimate interface among body, device and environment. Due to the extremely simple configuration of TENG, complicated manufacturing equipment is not necessary. Even home-made customized structure of TENG can meet the requirements of some specific applications, thereby making the technology possible to reach

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Table 1
Comparison of common clean energy harvesting methods.

Classification	Advantages	Disadvantages
Solar cell	Large DC current, High efficiency of hard devices	Limited energy source, Organic devices to be perfected
Biofuel cell	Bio-catalyst, Converting waste/excess chemical energy	Low efficiency, Limited electron transfer, Poor repeatability
Thermoelectric generator	DC output, Easy to scale down	High output resistance, Poor thermal characteristics
Electromagnetic generator	Large AC current, High efficiency at high frequencies	Generally rigid & bulky, Low power output of soft magnet
Piezoelectric nanogenerator	High sensitivity, Compatible with traditional microfabrication technology	Low output performance, High requirements for material preparation (Lattice orientation)
Triboelectric nanogenerator	Large AC voltage at low frequencies, Wide selection of materials, Wide range of energy sources, Simple structure, Low-cost	Pulse output, High impedance

millions of households. Besides, wearable TENG's low-cost and reliable energy conversion mechanism provide immediate opportunities to interpret the rich physiological information behind the output signals more directly.

Definitely, TENGs are not just "turning waste into treasure" in the field of wearable electronics. Herein, we will review the wearable TENG technology in a targeted and comprehensive manner, from its basic design, to its active function expansion, and then to the system powered by it. Furthermore, guided by routes established in the field of wearable electronics, exploration on more practical areas of TENGs will continue.

2. Wearable designs of TENGs

2.1. Wearable forms

At present, TENG has been brought into daily life in a variety of wearable forms [19]. The various styles of TENGs shown in Fig. 1 provide many possibilities in seamless integration with human body. Firstly, the electrification mechanism and basic working modes of the TENGs are the basis for building such devices. When two dissimilar materials contact each other under external force and produce effective friction, one material captures electrons form the other due to the difference in electron affinity at the interface. Then in separating process, a potential difference will appear and charge movement will occur if an external load exists. The open circuit voltage is at its maximum when the separation distance between the upper and lower materials in Fig. 1A (i) reaches farthest. The other three modes in Fig. 1A are variations of the contact-separation (CS) mode [20–25]. The friction process in the lateral-sliding (LS) mode is relatively more efficient [26,27]. In this approach, rather than immediate contact, two friction layers are rubbed in a tangential direction with a higher duty cycle of electrification [28,29], which endows the LS mode the ability for continuous output electricity and high-frequency applications [30,31]. More diversified structural designs are possible in the free-standing (FS) mode [32–34], and the single-electrode (SE) mode can better integrate with the human body or the surrounding environment [35–39].

On account that TENG needs effective friction between two dissimilar materials to start work, appropriate wearing part accompanied by body motions is critical to electrification. Such motions exist all the time during the subtle movements in daily life. Many auxiliary devices

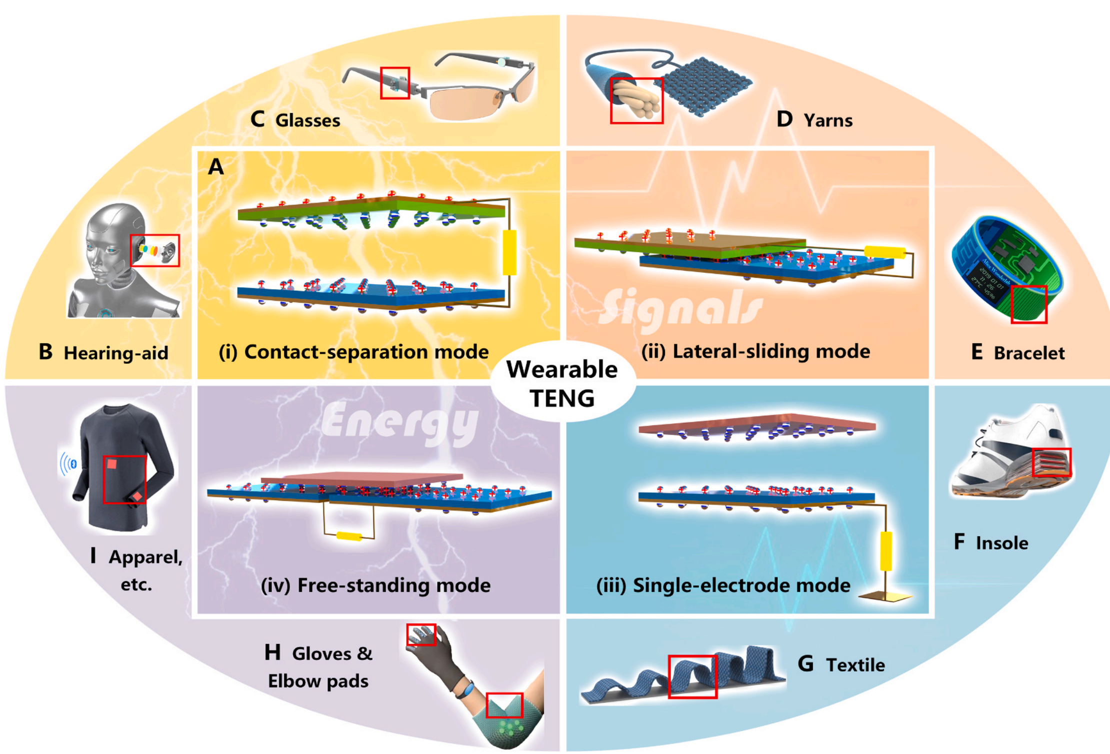

Fig. 1. Basic working modes and wearable forms of TENGs. (A) Four subdivided modes of TENGs. (B–I) Wearable forms/structures of TENGs: (B) TENG used for human/robotics auditory. Reproduced with permission [40]. Copyright © 2018, the Authors, published by AAAS. (C) Embedded-in glasses triggered by eye motion. Reproduced with permission [41]. Copyright © 2017, the Authors, published by AAAS. (D) Twisted into various yarns. Reproduced with permission [46]. Copyright © 2020, American Chemical Society. (E) Constructed into a sports bracelet. Reproduced with permission [55]. Copyright © 2018, Elsevier. (F) Embedded-in insoles driven by walking/running. Reproduced with permission [52]. Copyright © 2015, Springer Nature. (G) Woven into daily wearable textiles. Reproduced with permission [47]. Copyright © 2018, Elsevier. (H) Woven into daily protective gear. Reproduced with permission [57]. Copyright © 2019, The Authors, published by Springer. (I) Integrated into apparel in the form of embroidery or patch, etc. Reproduced with permission [59]. Copyright © 2020, the Authors, published by AAAS.

(Fig. 1B: hearing aids [40]; Fig. 1C: glasses [41]) allow for the monitoring of physiological signals and the conversion of the signals into digital information with the potentials to achieve more valuable functions.

In comparison, the relatively macroscopic body movements can induce vibrations and deformations of clothing. Thus, smart yarns/textiles appear and seize this part of energy [42–44]. Researchers design different modes to make the structures generate electricity when they come into contact with other clothing materials or human skin (Fig. 1D [45,46]; Fig. 1G [47]). Capitalizing on the relative-displacement between the core and shell of yarn is also an important means of energy collection/signal extraction [48]. In addition, the CS and LS between different parts of the smart fabric provide ideas for multi-mode TENG [49,50]. With respect to smart shoes, embedding TENG into the insole largely captures the mechanical energy generated during daily walking/running (Fig. 1F) [51–53].

Moreover, TENGs in the form of skin-attached accessories play a key role in the acquisition/conversion of kinetic message. Constructing TENGs into sports bracelets obtains body information and scavenges the energy of arm swing at the same time (Fig. 1E) [54–56]. Incorporating TENGs into various protective gears further endows TENGs more practical meanings, such as night illumination (Fig. 1H) [57], danger warning [58], remote communication (Fig. 1I) [59], etc. In short, the phenomenon of tribo-electrification is indeed ubiquitous and diverse.

Table 2 compares the working modes, materials and performances of various forms of recent wearable TENGs in detail. The results indicate that the output voltages are usually in the range of hundreds of volts, the currents reach the order of microamperes, and the output powers per square meter achieve the level of milliwatts. The non-contact mode is an extension of the existing ones [60,61] and further discussions about it appear in the next chapter. In order to meet the requirements of wearable devices, most of them select human-friendly metals, flexible and stable polymers, coated-textile or their combinations. Usually researchers adopt stretchable structural designs to metals [62,63], dope the polymer [64], or combine them together to achieve better effect. In the next section, more Adv. Mater. and related processes will leap to our sight.

2.2. Materials and processes

To build TENG into completely wearable format, considerations should not only include the flexibility/stretchability of the triboelectric materials and electrode materials, but also incorporate more practical characteristics adapted to actual diversified requirements, which has been illustrated in Fig. 2.

A breathable, biodegradable, antibacterial and all-nanofiber TENG receives public attention (Fig. 2A) [65]. With silver nanowire (Ag NW) sandwiched between polylactic-co-glycolic acid (PLGA) and polyvinyl alcohol (PVA), the fabricated micro-to-nano hierarchical porous structure has high specific surface area for contact electrification and numerous capillary channels for thermal-moisture transfer. Through adjusting the concentration of Ag NW and the selection of PVA and PLGA, the antibacterial and biodegradable capability of device are tunable.

The biocompatible and versatile TENG based on silk fibroin (SF) is also eye-catching (Fig. 2B) [66–68]. When proportionally mixing SF, polyacrylamide (PAM), graphene oxide (GO) and poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PEDOT:PSS), the resultant hydrogel are considerable stretchable and with no anaphylactic reaction on human skin. More interestingly, this conductive hydrogel exhibits a positive response and avoids the use of current collectors [69,70] when it works in a TENG.

Another porous-structural and skin-attachable TENG based on chitosan-diatom film has recently appeared (Fig. 2C) [71]. Both the diatom frustule and chitosan are naturally abundant and mass-producible from mega-scale ocean environments. The highly porous diatom frustule can serve as a biocompatible additive to greatly change electro-positivity and surface properties of chitosan films. Thus, the time averaged power density of the chitosan-diatom TENG is 3.7 times higher than that of the pure chitosan TENG.

Naturally rich cellulose has the opportunity to replace traditional flexible polymer substrates due to its superior bio-affinity and can be doped/modified to improve its triboelectric performance. In contrast to conventional TENGs that require current collectors to promote charge transfer, ions doped into natural nanofibrils can effectively fulfill charge transfer due to the separation and migration of cations and anions (Fig. 2D) [72]. Besides, the new principle and ultrasimple single-layer configuration enable them to be more easily integrated with other electronic components.

Currently, the difference in pair materials' inherent electron affinity, which can be tuned by chemical or physical methods, mainly determines the triboelectric performance. A "Genetically Engineered" TENG using recombinant spider silk proteins (RSSP) delivers programmable triboelectric property, multiple functionalization, large-scale-fabrication capability and transcendent output performance (Fig. 2E (i)) [73]. The triboelectric performance of RSSP drastically increases with the

Table 2
Comparison of wearable forms of TENGs.

Wearable forms	Working modes	Materials	Performance	Reference
Bracelet	Lateral-sliding (LS)	PTFE/PI/Cu	305 V, 300.4 μW, 69.3% energy transfer efficiency; > 50,000 cycles	[55]
Bracelet	Contact-separation (CS)	PPy/Cellulose paper/Nitrocellulose Membrane	60 V, 0.83 W/m^2@10 Hz; > 10,000 cycles	[174]
Fabric	CS	PDMS tube/Al wire/ZnO NWs/Au NPs	~ 40 V, 10 μA @50 N, single fiber; No degradation at 95% RH	[218]
Fabric	CS	Conductive fibers/PAN/PVDF	0.33 mg cm^{-1}; 40.8 V, 0.705 μA cm^{-2}, 9.513 nC cm^{-2}@5 N, 2.5 Hz	[46]
Fiber/Textile	CS & LS	Rayon fiber/Polyester fiber/Ni-coated textile	~ 25 V, 0.18 μA @9 N, 1 Hz; 3.9 μW @90 MΩ	[49]
Glasses	CS	Natural latex/PET/FEP/ITO	~ 750 mV (compared with electrooculogram approach ~ 1 mV)	[41]
Gloves	Non-contact	PDMS/Wool yarn/CNT cotton	Distinguish the direction of motions with resolutions of sub-mm level	[219]
Gloves & Textile	CS & Non-contact	STF/Ecoflex-Cl/PDMS-MWCNTs-Cl	27.05 mW m^{-2}, 10.4 V @10 MΩ under compression	[220]
Hearing aids	CS	Acrylic/PI/Au/FEP	110 mV dB^{-1}; Response from 100 to 5000 Hz	[40]
Insole	CS	Rubber/Cu/PET	~ 35 V, 0.4 μA @40 N, 4 Hz; 56 ms; > 1000 cycles	[51]
Insole	CS	Al/FEP/Cu	Continuous DC electricity of 7.34 W m^{-3}	[52]
Mask	CS	Acrylic/Al/Nylon/PTFE	190 V, 0.35 μA, 35 nC @ 2.4 Hz, 5 cm square	[151]
Sports gear	Single-electrode (SE)	Wire spring/Silicone rubber	~ 59.7 V, 2.67 μA, 23.7 nC, 2.13 μW @ 2.5 Hz, 6 cm single yarn	[57]
Textile	CS	Nylon/Stainless steel	7.84 mV Pa^{-1}; 20 ms; > 100,000 cycles; up to 20 Hz; > 40 washes	[59]
Textile	CS	PEDOT:PSS/PTFE/Al	2 W m^2@ stepping at 2 Hz; Strain up to 160%	[47]
Textile	CS	PTFE/PANI@WCT	~ 350 V, 45 μA @5 N, 5 Hz; No obvious degradation after mechanical tests	[221]
Yarns & Wristband	CS	Ag-coated nylon yarn/Silicone rubber	230 mW m^{-2}@3.24 mm square; > 50,000 cycles	[45]

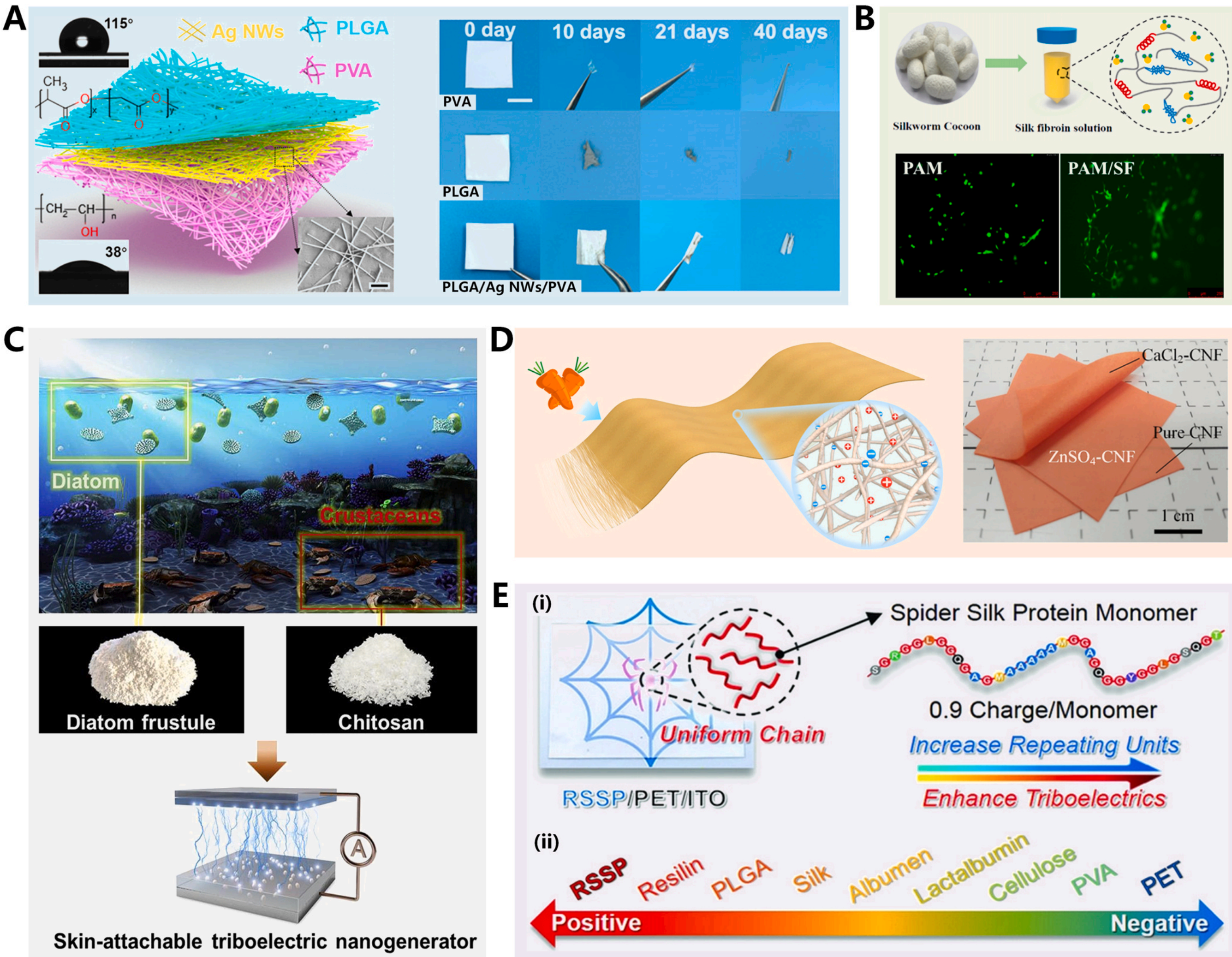

Fig. 2. Latest material selections of wearable TENGs. (A) All-biodegradable-nanofiber TENG and its in vitro biodegradation tests. Reproduced with permission [65]. Copyright © 2020, the Authors, published by AAAS. (B) Silk fibroin material and related fluorescent staining cell culture. Reproduced with permission [66]. Copyright © 2020, American Chemical Society. (C) Chitosan-diatom-based TENG. Reproduced with permission [71]. Copyright © 2020, Elsevier. (D) TENG based on ion-doped natural nanofibrils. Reproduced with permission [72]. Copyright © 2020, American Chemical Society. (E) (i) "Genetically Engineered" TENG using RSSP. (ii) Triboelectric series of various biomaterials. Reproduced with permission [73]. Copyright © 2018, Wiley-VCH.

increment of repeating units.

Fig. 2E (ii) shows the relative ability ranking of positive (losing electron) or negative (gaining electrons) of various biomaterials [73]. These materials have excellent biocompatibility and the constituted devices possess good electrical properties at the same time through the materialogy design, which follows the goal of "wearability" and "popularization" for TENGs. In other words, while pursuing the electrical performance of TENGs, the friendly relationship between human and devices is worthy of our considerations. Therefore, combining the mature wearable materials in Table 2 and these new biomaterials can yield more diversified pair materials of TENGs with greater electronegativity differences and stronger competitiveness towards wearable market.

Fig. 3 summarizes several promising processes in recent years. In 2016, two-step sponge-like composite based on sacrificial templates gives conductive elastic polymer more potential for triboelectrification (Fig. 3A) [74]. The stretchable porous nanocomposite (PNC) consists of a multiwalled carbon nanotubes (CNTs) network and a polydimethylsiloxane (PDMS) matrix. In response to mechanical forces applied onto the PNC, the deformation of the elastic matrix results in contact electrification between the exposed CNTs and the PDMS matrix on the inner surface of the deformed cavities. Compared with traditional solid materials, PNC exhibits a smaller equivalent Young's modulus and undergoes a greater degree of deformation under the same external stress [75], thus possesses a better sensitivity. In addition, the interconnected porous network inside the PNC [76] results in better skin-attached breathability. Other soluble powder templates, such as sugar [77], can achieve the same effect.

Researchers exploit hybrid three-dimensional (3D) printing approach to make composite resin with both electrification layer and electrode [78]. Fig. 3B reveals the printed part with high accuracy and ultra-flexibility. The scanning electron microscope (SEM) analysis about the micro-morphology of the ultraflexible part clearly shows a layer-upon-layer structure, which further proves its easy/extra controllability.

Fig. 3C depicts a liquid-metal-based process by employing Galinstan as the electrode and silicone rubber as the triboelectric and encapsulation layer [79]. The simple mold process offers solutions for personalizing the wearable shape of TENGs. Besides, the liquid form ensures that the electrode remains continuously conductive under severe deformations, such as stretching with a strain as large as ~ 300%. On this basis, liquid metal/polymer core/shell fibers structure is expected to become a large-scale [80] and amphibious [48] approach.

Skin-like TENG based on stacked hybrids of elastomers and

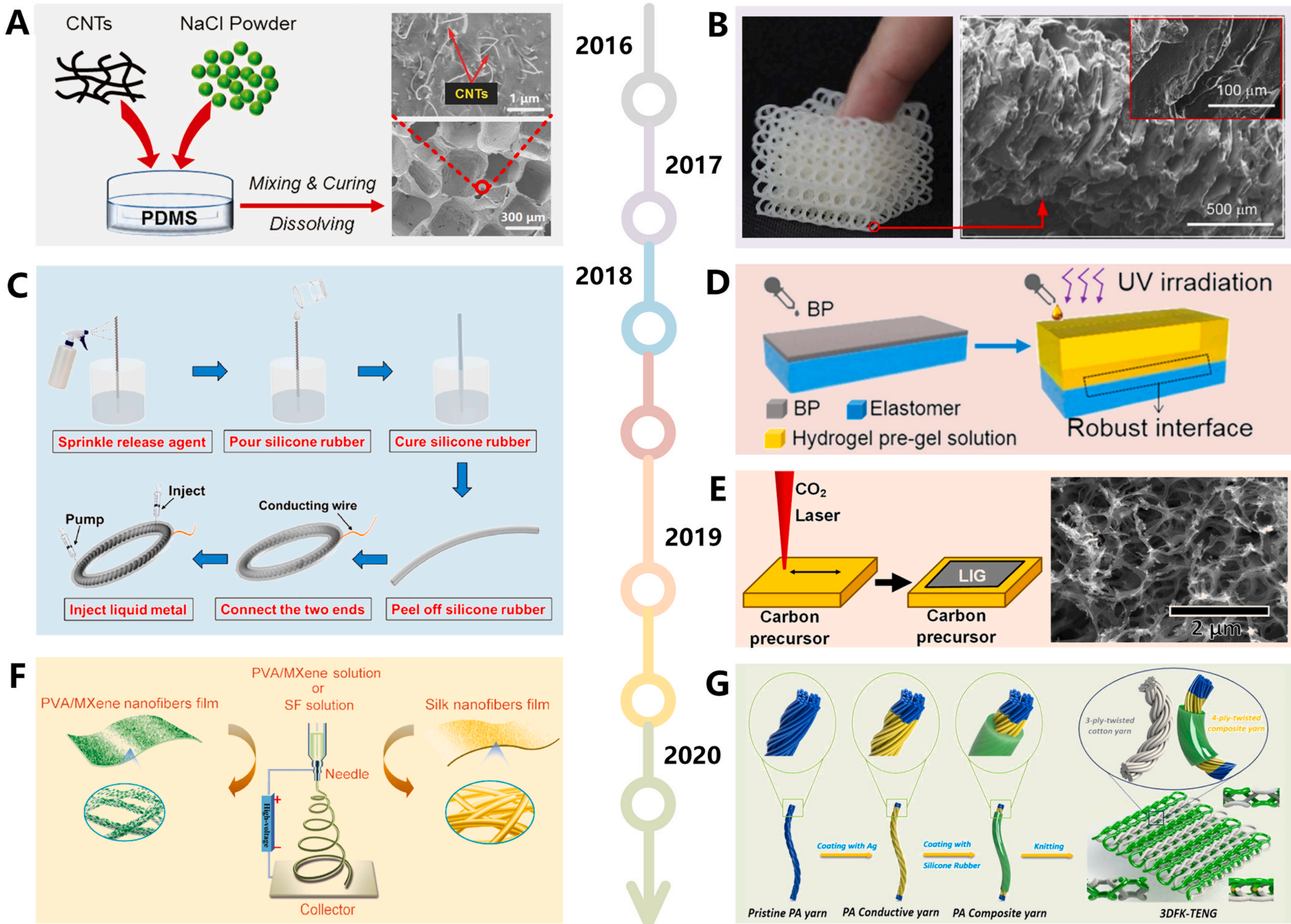

Fig. 3. Recent processing technologies of wearable TENGs. (A) Porous conductive elastomer process. Reproduced with permission [74]. Copyright © 2016, Wiley-VCH. (B) TENG made by hybrid UV 3D printing. Reproduced with permission [78]. Copyright © 2018, Elsevier. (C) Fabrication process of liquid-metal-based TENG. Reproduced with permission [79]. Copyright © 2018, American Chemical Society. (D) Fabrication approach of TENG enabled by elastomer/hydrogel hybrids. Reproduced with permission [81]. Copyright © 2018, American Chemical Society. (E) LIG-based TENG. Reproduced with permission [86]. Copyright © 2019, American Chemical Society. (F) All-electrospun TENG. Reproduced with permission [89]. Copyright © 2019, Elsevier. (G) Processing technology of 3D interlock fabric TENG. Reproduced with permission [91]. Copyright © 2019, Elsevier.

hydrogels also achieves ultrahigh stretchability (~ 1160%, [69]). However, the hydrophilic hydrogel and the generally hydrophobic elastomers naturally form a weakly bonded interface. Tough interfacial bonding between the hydrogel and elastomers by interface modification ensures the stable mechanical and electrical performance of the TENGs (Fig. 3D) [81]. Inherent ductility and rich hydrogen bonds make it suitable for ultra-thin skin-conformal [81] and self-healing application scenarios [82]. Moreover, the improved ion-conducting hydrogels/ionogels could work over a wide temperature range from −20 °C to 110 °C and avoid solidification or dehydration of the solvent [83].

Laser-assisted processing methods have deeply affected many fields. Interestingly, laser-induced graphene (LIG) could be in situ synthesized on a carbon-based precursor during one-step laser writing [84]. The composites exhibit the triboelectric properties of the carbon source and the high conductivity of LIG to form a high-performance TENG electrode [85]. Besides, temperature above 2500 °C under laser exposure results in the rapid outgassing of non-carbon elements that gives the LIG a porous microstructure and high surface area (Fig. 3E) [86,87]. Then, selectively transfer of LIG onto other substrates can empower it with more attributes [88].

Electrospinning, a typical technique for nanofiber manufacturing, has motivated ever-increasing interest. Utilizing this fast and efficient approach, Fig. 3F demonstrates a flexible and robust MXene-SF-based all-electrospun TENG [89]. Meanwhile, the electrospinning nanofiber film serves as highly responsive layer due to its large specific surface area.

Combining TENG, textile material (for its breathability, washability, flexibility, lightweight, etc. [90]) with wearable electronics shows great application prospects in this coming intelligent era. Zhong Lin Wang's group design a 3D double faced interlock fabric TENG (3DFIF-TENG) by using a double needle bed flat knitting machine technology (Fig. 3G) [91]. It is worth noting that this TENG is substrate-free and can generate electricity by bending and stretching itself. Besides, the 3D structural design and the optimized special structure with warp inserting and weft inserting in the middle layer make the 3DFIF-TENG more multifunctional.

The biocompatibility of materials and processes is the primary prerequisite for TENGs to face the wearable field. More suitable material properties and related process development should be designed according to specific needs, which may be more recognized by the public than simply pursuing the electrical performance of TENGs. Only after the basic design of TENGs reaches the standard, we can truly seek more application scenarios and practical values of them.

2.3. Performance optimization

In addition to developing more bio-affinity properties of materials and reducing process complexity/cost, this section presents some other specific designs that can further improve the TENG's performance.

The utilization of surface structure and material modification has been considered as effective ways to improve performance [92–96]. A wrinkle structure TENG made by fluorocarbon plasma treatment enhances the current and surface charge density by 810% and 528%, respectively, compared with the untreated one [97]. Fig. 4A presents a simple method for fabricating two-dimensional and nested hierarchical wrinkle structures on PDMS surface via one-step C_4F_8 plasma treatment [98]. Such wrinkle structures can be controlled by radio frequency (RF) power, treatment time and compression strain.

Through the facile replication of the surface morphology of natural plants, the interlocking microstructures are generated on triboelectrification-layers to enhance surface charge densities (Fig. 4B) [99]. Specifically, the whole process is realized by two-step templating approach: the first molding of the original leaf allows the fabrications of substrate (such as PDMS) with reversed patterns, and another molding process on the resultant PDMS patterns yields the replication of surface morphology of plants on PDMS substrate. Along with the adoption of polytetrafluoroethylene (PTFE) tinny burrs on the microstructured triboelectrification surface, the sensitivity for pressure measurement achieves 14-fold increase. In addition, such bionic surface gives the device the characteristics of waterproof [100] and self-cleaning [101] and the reversed patterns obtained by one-step templating method can meet other requirements of performance improvement [22,102].

Fig. 4C illustrates the essentiality of the shield film for the performance of the TENG-based sensor [103]. The touching objects (glove, fingers, etc.) may naturally carry some charges on their surfaces, which induce the output signals as well. Furthermore, the contact between touching object and the top surface of the device may also lead to the electrification process. At this time, the role of the shield film in electrostatic interference and repeatability improvement is particularly indispensable.

Fig. 4D presents a TENG based on the rigid-flexible coupling design using the acrylate structure glue (ASG, the rigid layer) and the silicic acid gel (SAG, the soft layer) as the triboelectric pairs [104]. It can be observed that the combination of flexibility@rigidity achieves the highest output owning to the fullest contact of triboelectric surface. As for the combination of flexibility@flexibility, the force position of the device is locally inhomogeneous in most cases, which leads to local contact and low electrical output. For the combination of rigidity@rigidity, the rigid surfaces that are hard to deform cause insufficient interface contact.

Mechanical designs in wearable skin-integrated/epidermal electronics play a vital role in the device performance ranging from flexibility, to robustness, and to the overall electrical property. Fig. 4F reveals the relationships between effective working area and the electrical performance of epidermal TENGs (e-TENGs) [105]. The results show that the electrical outputs and mechanical properties are highly relevant with the working area. Advanced serpentines based on cobweb-pattern design allow e-TENG devices to exhibit great energy harvesting behaviors and excellent stretchability.

In short, we can simulate/utilize the exquisite microstructure from nature/biology to improve the output of TENGs without sacrificing the process complexity. Solutions to make TENGs better merge into

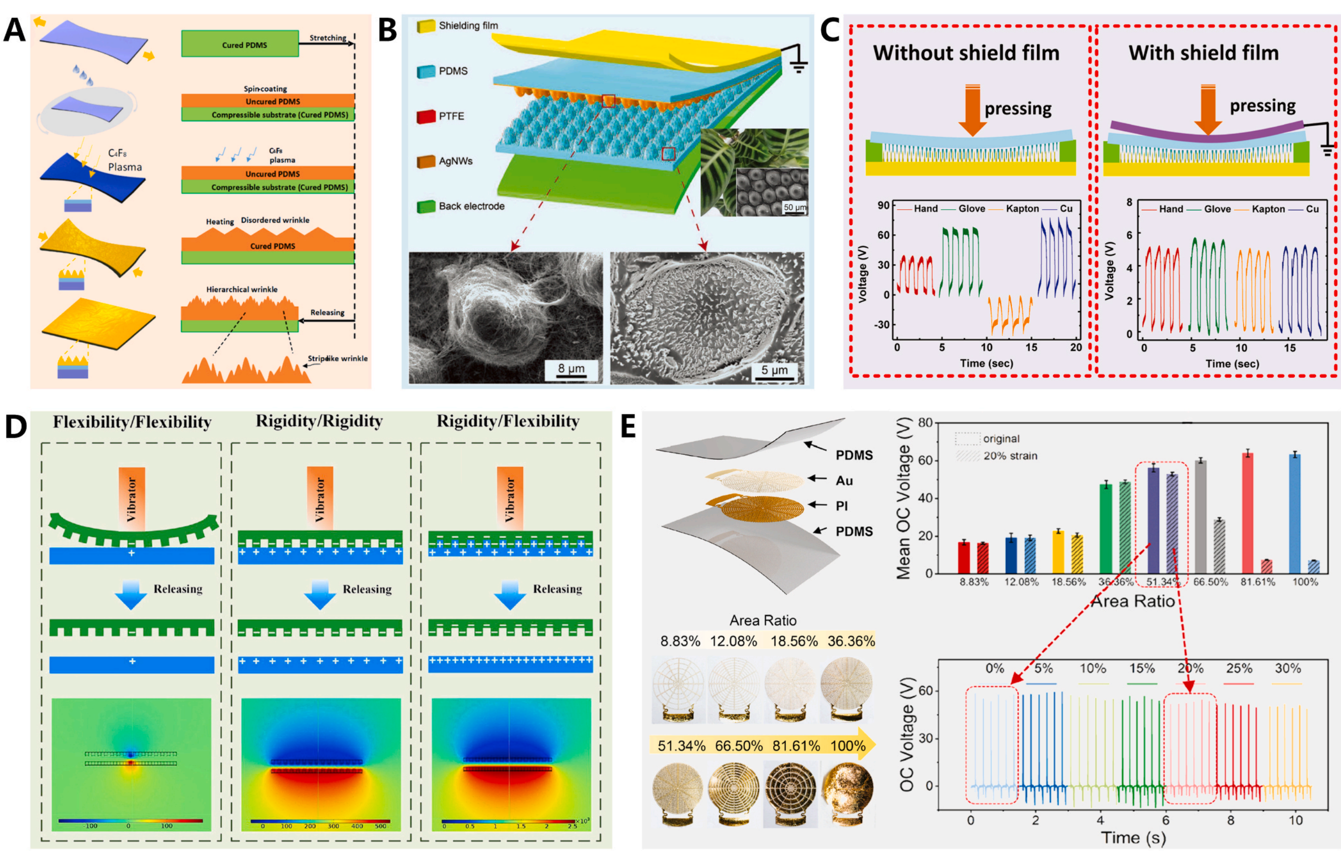

Fig. 4. Optimization for wearable TENGs. (A) Flowchart of hierarchical wrinkle structure to increase the efficiency of triboelectricity. Reproduced with permission [98]. Copyright © 2017, IOP Publishing. (B) Bioinspired TENG designed to enhance triboelectric effects. Reproduced with permission [99]. Copyright © 2019, Wiley-VCH. (C) Shield film design to screen the electrostatic interference. Reproduced with permission [103]. Copyright © 2018, Wiley-VCH. (D) TENG based on rigid-flexible coupling design. Reproduced with permission [104]. Copyright © 2020, Elsevier. (E) Mechanics designs-performance relationships in epidermal TENGs. Reproduced with permission [105]. Copyright © 2020, Elsevier.

practical applications, lie in the optimization of the structural design, such as coordinating the stress mismatch of contact interface, reducing the environment noise/interference, etc.

3. Wearable TENG-based devices

In this chapter, we will highlight the signal conversion ability of wearable TENGs, that is, TENGs can directly convert rich information behind human body into more intuitive and useful electrical signals [106–110]. Without external power supply, the active sensors based on TENG are suitable for precise auxiliary senses, physiological detection, disease prediction, outdoor danger warning, etc. In the fields of actuators, especially in the biomedical applications, the stimulus signals from wearable TENGs can assist in drug delivery, nerve stimulation and construction of artificial reflex arc. Besides, this type of signal conversion largely reduces the complexity and power consumption of the traditional human-machine interfaces/interactions.

3.1. Active sensors

When accompanied by rhythmic or arbitrary movements of the human body, wearable TENGs directly sent out electrical outputs in the form of pulses during the effective friction processes. Not only the pulse amplitude [111], but also the polarity, periodicity, waveform details [112,113], etc. can provide a reliable data source for assisting living, rehabilitation, surveillance, etc., thereby realizing the sensing functions without external energy supply.

Fig. 5A illustrates the case of non-contact TENG as a proximity sensor [75]. During continuous movements, the successive friction electrification between the limbs and the surrounding environment causes the interface to be charged with saturation. Thus, when the charged object approaches/leaves the device attached on the skin, the induced charges on the device surface change, generating an induced current of the corresponding polarity. Cooperating with other dimensions of mechanical sensing, it can monitor and correct the athlete's training posture.

The TENG inspired by fingerprint patterns in Fig. 5B [114] is capable detecting sliding direction and speed with the help of the four spiral electrodes. Such sliding tactile sensing adopts the frequency rather than the amplitude to detect the signal to avoid interference from the environment.

In terms of gesture trajectory sensing, some drawbacks exist in state-of-art approach of integrated sensing units into arrays: e.g. the trade-off between resolution, effective area, and power consumption [115].

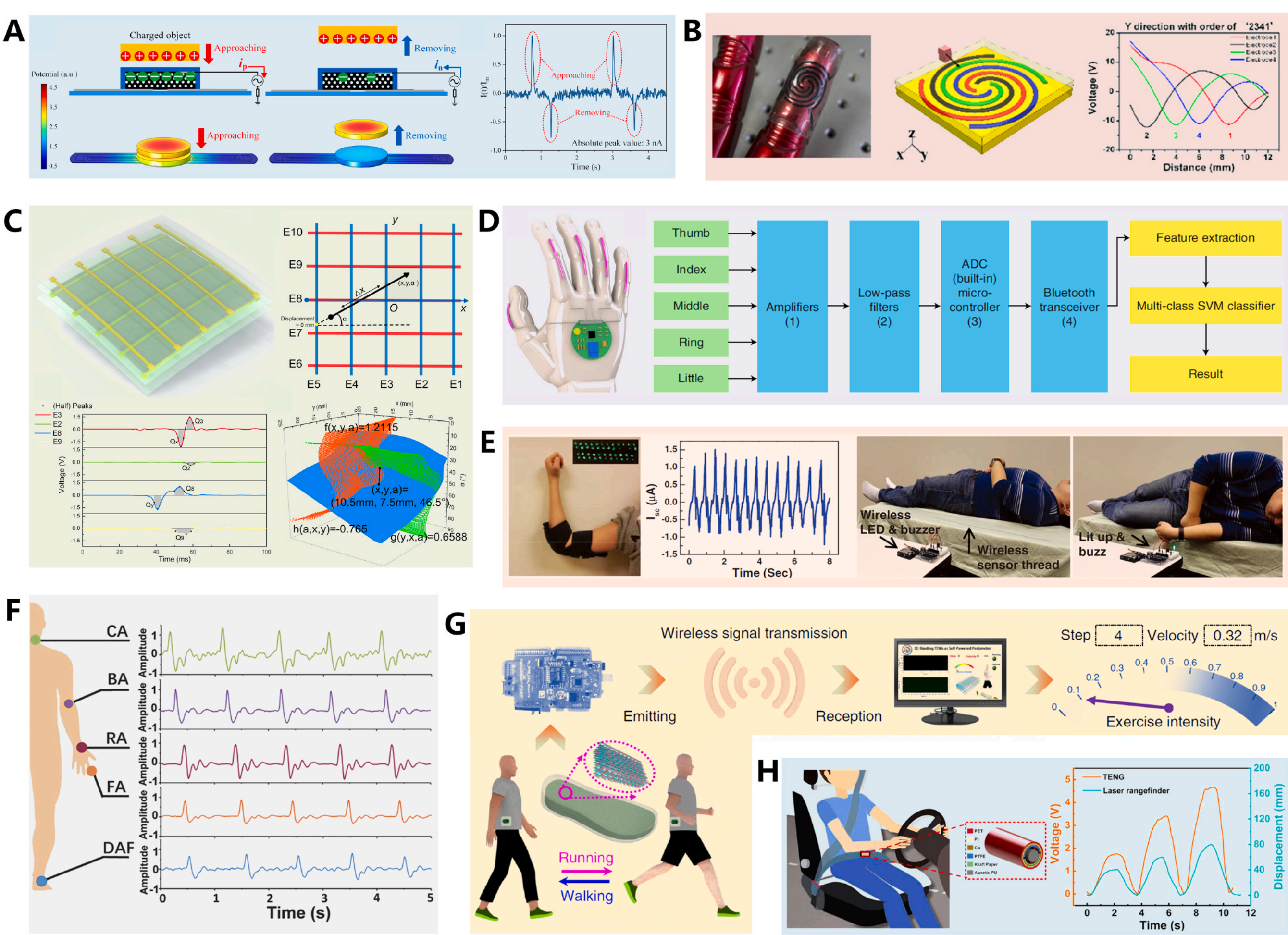

Fig. 5. Wearable TENGs for active sensing. (A) TENG serves as a proximity sensor. Reproduced with permission [75]. Copyright © 2019, Elsevier. (B) Fingerprint inspired TENG used for sliding direction sensing. Reproduced with permission [114]. Copyright © 2018, Elsevier. (C) Self-powered digital-analog hybrid e-skin based on TENG. Reproduced with permission [116]. Copyright © 2019, Elsevier. (D) Sign-to-speech translation using machine-learning-assisted stretchable TENG arrays. Reproduced with permission [118]. Copyright © 2020, Springer Nature. (E) Cloth-based TENG applied to human-interactive sensing. Reproduced with permission [119]. Copyright © 2016, Wiley-VCH. (F) Ultrasensitive pulse sensor based on TENG. Reproduced with permission [123]. Copyright © 2017, Wiley-VCH. (G) An intelligent footwear system based on 3D braided TENG. Reproduced with permission [124]. Copyright © 2020, Springer Nature. (H) Smart safety belt enabled by TENG. Reproduced with permission [127]. Copyright © 2019, Elsevier.

Fig. 5C presents a self-powered digital-analog hybrid e-skin for measuring noncontact linear planar displacement which achieves a high resolution of (0.75 mm, 1.07 mm, 2.20°) in a large area of 100 cm^2 in three degrees of freedom [116]. It uses the integral along peak width at half height of the voltage waveforms to represent the transferred charge, in order to enhance the signal noise ratio by obviating the noise signal at low magnitude. In addition, coupled piezoelectric module can enrich the perception dimension, i.e., the dynamic pressure measurement [117].

In addition to being used in machine touch and distance perception, technology-mediated approaches could mitigate the communication barrier between signers and non-signers. The wearable sign-to-speech translation system of Fig. 5D, is composed of yarn-based TENG sensor arrays and a wireless printed circuit board [118]. By incorporating with machine learning, it achieves high standards in terms of recognition rate (98.63%) and recognition time (< 1 s).

Besides the examples of "auxiliary receptors" highlighted above, TENG can also emerge as physiological monitoring and assisted recovery in daily life. The stretchable TENG textile in Fig. 5E worn on a human's elbow scavenges energy from the flexion and extension of the elbow on the one hand. On the other hand, when a person moves to the edge of bed and triggers the active triboelectric thread, the transmitter will wirelessly transmit the warning signal to the receiver by buzzing and powering up the light-emitting diodes (LEDs) to care the patient or elders [119]. Besides, assembling the TENG array on the bedsheet could enable higher-resolution sleep behavior monitoring and sleep quality evaluation [120]. Another idea is to combine photoluminescent [121]/electroluminescent [122] materials for visualized sensing/warning.

A flexible ultrasensitive pulse sensor (SUPS) based on TENG proposed in Fig. 5F owns excellent output performance (1.52 V), high peak signal-noise ratio (45 dB), long-term performance (10^7 cycles), and low cost price [123]. Attributed to the crucial features of acquiring easy-processed pulse waveform, SUPS can be integrated with a Bluetooth chip to provide accurate, wireless, and real-time monitoring of pulse signals of cardiovascular system on a smart phone/personal computer (PC). Another triboelectric all-textile sensor array can be incorporated into different sites of clothes for esthetic design and used to simultaneously monitor the pulse and respiratory signals in real time [59]. Such a design can help distinguish between healthy individuals and those with cardiovascular disease or sleep apnea syndrome because of its capability to capture detailed information.

Sensors with stable performance, ultralow power consumption, and reliable sensing capability are significant for wearable outdoor monitoring. Thanks to being encapsulated in a rubber sole, the three-dimensional braided TENG in Fig. 5G can not only isolate environment interferences and protect against contamination, but also convert exercise actions into real-time voltage signals [124]. Then, the step number, average velocity, and exercise intensity will be calculated and displayed on the software output interface. Moreover, it can light up safety indication signs on the human body in dark environments to distinguish individuals to passing drivers and send distress signals remotely and wirelessly when potential hazards approach.

When it comes to driving status monitoring, it is highly desirable to ensure safety and prevent traffic accidents [125,126]. Fig. 5H shows a smart safety belt to monitor the forward position and turning actions of the driver, which achieves high sensitivity (0.89 V/cm^2) for strain measurements in the large strain domain (40–100%) [127]. This work enlightens an effective approach to integrate TENG sensors seamlessly into existing living environment for actual life supervising, thereby expanding their application value in the field of wearable electronics.

To sum up, wearable TENGs have achieved a good detection coverage ranging from heartbeat/pulse signals to limb flexion and extension amplitude, and even assisted in the realization of human sensory functions. By further optimizing the sensitivity and responsivity of active sensors, we can track physiological signals with higher frequency and more precision in real time. Utilizing the electrochemical activity of the friction layer material [128], more kinds of physiological signals (such as the ingredients in the secretions [129] or respirations [130,131] to reflect the health status of body) and parameters at human-environment interface (such as humidity [132], amenity [133], ammonia [134], nitrogen dioxide [135], etc.) could be detected. Furthermore, more stringent material selection and design of tolerance to in-vivo environment can lead TENGs to implantable application [136,137], with potentials in detecting more health indicators [138] and predicting various chronic diseases [123].

3.2. Actuators

In recent years, wearable TENG-driven actuators technology has made major breakthrough in the biomedical field. For one thing, high-voltage pulse output could directly drive some medical instruments. For another thing, as "auxiliary receptors" mentioned above, TENGs transform external stimuli into "action potentials", which could be read and transmitted by organism, then regulate the body.

Transdermal drug delivery (TDD) systems with feedback control have attracted extensive research and clinical interests owing to their unique advantages of convenience, self-administration, and safety. Here, Fig. 6A portrays a wearable iontophoretic TDD system driven and regulated by the energy harvested from biomechanical motions, which is proposed for closed-loop motion detection and therapy [139]. Meanwhile, the hydrogel-based conformal skin patch enables noninvasive TDD. Besides, Fig. 6B proposes a self-powered adhesive skin patch with bendable microneedle array for TDD [140]. The microneedle and triboelectric patches are connected with three dry adhesive patches to make the whole wearable device able to be fixed onto the curved skin surface. The triboelectric contact surface with PDMS micropatterned structure can enhance the performance.

Modulation of peripheral nerves is an emerging field for neuroprosthesis and therapeutic of muscle function loss. TENGs show promising performance as a power source of a neuro-stimulator since the output of TENGs provide direction stimulation of a nerve. In Fig. 6C, to achieve battery-free neutral electrodes, the sling interface connected with the TENGs is implanted on a sciatic nerve to selectively activate the tibialis anterior (TA) muscle [141]. Furthermore, it demonstrates stimulation of the common peroneal (CP) nerve using the TENGs combined with a pair of Pt/Ir wires to control a TA muscle. Operation of the device could accurately control the degree of muscle activation. Another work introduces a novel water/air hybrid TENG (WATENG) to overcome current drawbacks of conventional TENGs (Fig. 6D) [142]. The output charge amplified by the suspended dielectric thin film is able to induce plantar flexion (PF) and ankle dorsiflexor (DF) via tibial and CP nerve branches. A detailed comparison between the biphasic square waveform and exponentially decreasing waveform verifies the high effectiveness of WATENG for nerve stimulation. Further, Lee et al. recently proposes a direct muscle stimulation using TENG's current (35 μA) integrated with a multiple-channel intramuscular electrode [143].

TENGs can not only perceive information as mentioned in the previous section, but also learn and remember information like a human. As inspired by somatosensory signal generation and neuroplasticity-based signal processing, Fig. 6E unveils a tactile sensor which can actively produce signals with various amplitudes on the basis of the history of pressure stimulations because of their capacity to mimic neuromorphic functions of synaptic potentiation and memory [144]. The reduced graphene oxides (rGOs) embedded in the friction layer act as electron body traps and play a key role in the neuroplasticity. The stacked structure in the friction layer is able to mediate the retention time of the information.

An alternative way is to choose neuromorphic devices (such as synaptic transistors) to better learn and remember, and use TENG to achieve more biological functions. Fig. 6F emulates an energy scavenging artificial nervous system for detecting rotational movement to mimic the functions and mechanisms of the biological semicircular

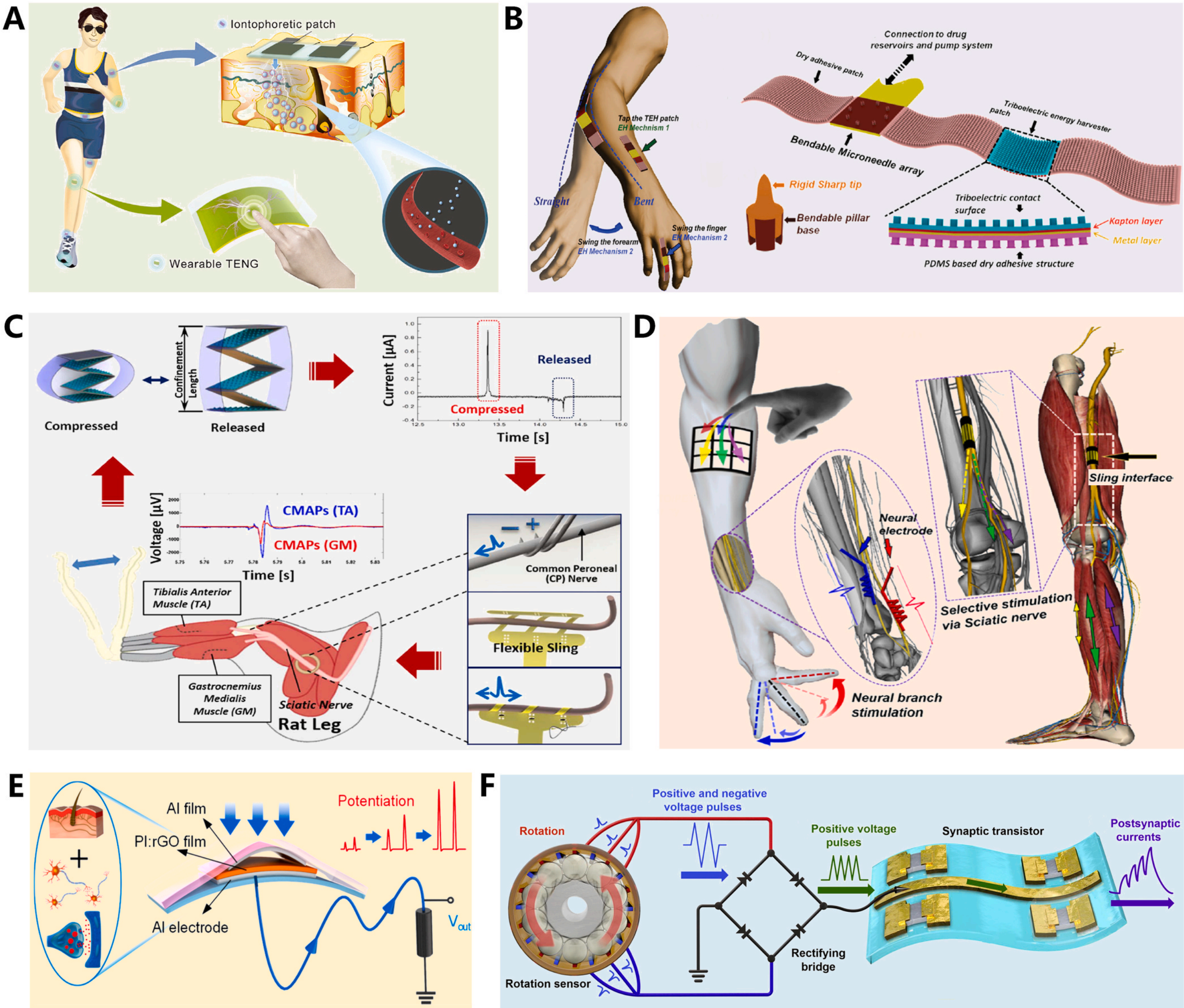

Fig. 6. Wearable TENG-based actuators. (A) TENG-regulated iontophoretic TDD system. Reproduced with permission [139]. Copyright © 2019, Wiley-VCH. (B) Wearable adhesive skin patch for TDD. Reproduced with permission [140]. Copyright © 2016, Wiley-VCH. (C) Modulated control of tibialis anterior muscle based on TENGs. Reproduced with permission [141]. Copyright © 2017, Elsevier. (D) Battery-free neuromodulator for peripheral nerve direct stimulation. Reproduced with permission [142]. Copyright © 2018, Elsevier. (E) Tactile TENG with learning and memory. Reproduced with permission [144]. Copyright © 2019, American Chemical Society. (F) Energy scavenging artificial nervous system. Reproduced with permission [145]. Copyright © 2020, Elsevier.

canals [145]. By integrating synaptic transistors with TENG [146,147], the system is able to detect movements on the coordinates in real time, which has promising applications including neuromorphic computation, neurorobotics and neuroprosthetics [148,149]. Moreover, the artificial “afferent nerve” should select intermediate components to improve the matching between TENGs and “synapses” and the postsynaptic current could be amplified and connected to “efferent nerve” to realize the complete “reflex arc” function [150].

TENG-driven actuators are thriving as well in other fields, such as TENG air filter for $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) removal [151], tunable optical modulator by coupling a TENG and a dielectric elastomer [152], implantable fields like photothermally tunable TENG for tissue repairing [153], and in-vivo cancer therapy by a magnet TENG [154], which shows that this technology has become more popular and begun to merge into our lives. For TENG’s optimization in this respect, the energy-driven schemes need higher output density, and the signal-driven schemes need better signal quality.

3.3. *Smart interfaces/interactions*

In addition to serving and promoting human beings through the forms of sensing and actuating, the pulsed output of wearable TENGs can also act as the medium between human and machine. Usually, the interaction between human and machine needs complex processing interface, while TENGs realize the interaction in a bio-friendly and autonomous way by using the information in human body [155].

In human-machine interaction, robotic hands can work like human’s hands and perform in a more powerful or delicate manner in certain situations. Operating robotic hands via human gesture instead of handle or button will make this human-robot interface more natural and precise. Fig. 7A shows the design of a joint motion triboelectric quantization sensor (jmTQS) for constructing a robotic hand synchronous control system [156]. Based on the ultrahigh sensitivity to mechanical displacement, the jmTQS designed as grating-sliding mode can directly quantify a joint’s flexion-extension degree/speed. The direct quantization and intuitionistic mapping at the sensing stage greatly simplify the

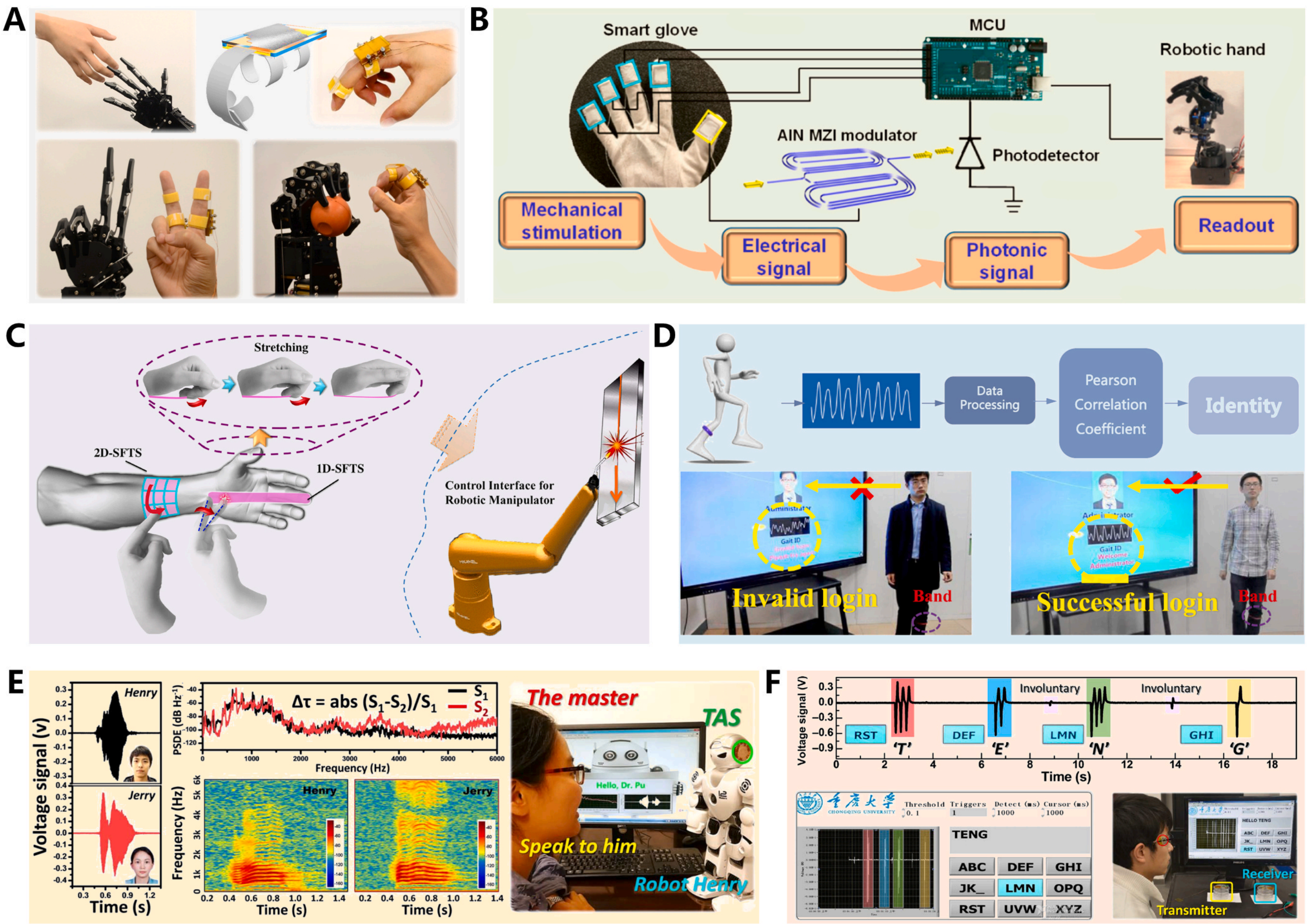

Fig. 7. Wearable TENG-based interfaces/interactions. (A) Gesture control of a robot joint via TENG. Reproduced with permission [156]. Copyright © 2018, Elsevier. (B) Real-time robotic hand control based on wearable THMI-nanophotonic systems. Reproduced with permission [157]. Copyright © 2020, American Chemical Society. (C) Wearable flexible patches used as 3D motion control interface for robotic manipulator. Reproduced with permission [158]. Copyright © 2018, American Chemical Society. (D) TENG band for identity recognition. Reproduced with permission [160]. Copyright © 2018, Elsevier. (E) Application of the TAS for imitating an auditory system. Reproduced with permission [40]. Copyright © 2018, the Authors, published by AAAS. (F) Application of the msTENG in a hands-free typing system. Reproduced with permission [41]. Copyright © 2017, the Authors, published by AAAS.

signal processing and classification algorithms, which are key features required for achieving the natural, high-precision and real-time interface.

Various triboelectric-human-machine interfaces (THMIs) conventionally use electrical readout and produce pulse-like signals due to the transient charge flows, leading to unstable and lossy transfer of interaction information. To address this issue, Fig. 7B uncovers a strategy by equipping THMIs with robust nanophotonic aluminum nitride (AlN) modulators for readout [157]. The electrically capacitive nature of AlN modulators enables THMIs to work in the open-circuit condition. Meanwhile, the interaction information is transduced from THMI's voltage to AlN modulators' optical output via the electro-optic Pockels effect. Leveraging the design flexibility of THMIs and nanophotonic readout circuits, various linear sensitivities are independent of force speeds in different interaction force ranges.

The flexible triboelectric sensor (FTS) patch in Fig. 7C can be divided into a two-dimensional (2D) FTS for in-plane robotic movement control and a one-dimensional (1D) FTS for out-of-plane control [158]. The 2D FTS, similar to the design in Fig. 5C, could track the continuous sliding information on the fingertip, e.g., trajectory, velocity, and acceleration. Combining 2D FTS with 1D FTS can form 3D motion control interfaces for a robotic manipulator in diversified multifunction operations.

Since each individual has distinct characteristics, monitoring such information by TENG can enable identity recognition [159]. Fig. 7D reports a smart band that can recognize human identity through gait pattern achieved by detecting muscle activity [160]. The band can quantitatively detect walking step, speed and distance, and is suitable for personal computer login, employee clock in, etc.

Mechnosensational HMIs can greatly extend communication channels between human and external devices in a natural way. Thereinto, auditory system is an efficient and straightforward communication strategy for connecting human beings and robots. Fig. 7E describes a triboelectric auditory sensor (TAS) with ultrahigh sensitivity (110 mV/dB) [40]. Designing the inner boundary architecture with systematic optimization achieves broadband response from 100 to 5000 Hz. When worn on intelligent robotic devices, TAS can perform high-quality music recording and accurate voice recognition. In the case of eye motions, the mechanical micromotion of the skin around the corners of eyes is a good trigger signal source. The mechnosensational TENG (msTENG) in Fig. 7F is capable of effectively capturing eye blink motion with a super-high signal level (~ 750 mV) compared with the traditional electrooculogram (EOG) approach (~ 1 mV) [41]. When mounted on the glass arms, the noninvasive micromotion sensors can construct two practical HMI systems: the smart home control system and the wireless hands-free typing system.

Therefore, TENGs not only reduce the complexity and power consumption of the interfaces, but also achieves better sensitivity and affinity. Next, we could consider shortening TENGs' response delay and improving their control accuracy. With the innovative assembly of wearable TENGs in other body parts, we can foresee great potential of TENG-based interfaces in continuous real-time robotics control and virtual/augmented reality interaction.

4. Wearable TENG-powered systems

In addition to the collecting valuable signals from human body to greatly facilitate and enrich our lives, TENG as an effective energy harvesting method, can convert kinetic energy into electricity to power the whole electronic systems for their continuous operation [19, 161–164]. We should not only optimize the performance of TENG to get the standard of powering system, but also consider the system integration level (including process, configuration, etc.) to meet the needs of users. In this respect, we introduce the wearable TENG-powered systems from the performance and process levels:

4.1. Performance-level integration

Firstly, TENGs' optimization and improvement enable them to mitigate the dependence on external energy supply in many fields. As energy consumption is a crucial challenge in the field of wireless wearable biosensors, we really need a battery-free wearable platform that efficiently extracts power from body motions. Through a flexible printed circuit board (FPCB)-based freestanding TENG (FTENG), the system worn on the side torso (Fig. 8A) realizes continuous biosensing [165]. Benefiting from seamless system integration and efficient power management (PM), the FTENG displays a high power output of ~ 416 mW m^{-2}, which is sufficient to power multiplexed sweat biosensors and wirelessly transmit data to the user interfaces. Such an FTENG-powered wearable sweat sensor system (FWS^3) uses PTFE and copper as tribo-pairs to obtain a strong electrification effect. Besides, the inter-electrode distance is optimized through transferred charge density studies of the FTENGs.

Fig. 8. Wearable TENG-powered systems. (A–C) Performance-level integrations: (A) Battery-free FWS^3 for wireless and noninvasive molecular monitoring. Reproduced with permission [165]. Copyright © 2020, the Authors, published by AAAS. (B) Wearable self-powered lactate sensor. Reproduced with permission [166]. Copyright © 2017, Elsevier. (C) TENG enabled heart-rate monitoring. Reproduced with permission [167]. Copyright © 2017, American Chemical Society. (D–F) Process-level integrations: (D) Weaving DC F-TENGs and Yarn SC into self-charging fabric. Reproduced with permission [172]. Copyright © 2020, American Chemical Society. (E) Paper-based self-charging power wristband. Reproduced with permission [174]. Copyright © 2019, American Chemical Society. (F) Stretchable-electrode-based energy supply system. Reproduced with permission [175]. Copyright © 2017, Wiley-VCH.

Considering the adaptability and flexibility of self-powered systems to fit human body shapes and postures, Fig. 8B assembles a gelatin-based TENG and a noninvasive sensor on the insole and skin, respectively, for real-time monitoring the physical condition of body [166]. In addition to providing the energy required for electrochemical detection of biosensor, the electric output of the TENG can control the size and density of the electrocatalytic nanoparticles on the sensing electrode. Furthermore, the as-prepared wearable sensing system exhibits significant selectivity and sensitivity toward lactate detection. With the operation of the TENG for less than one minute, the generated electricity is sufficient for the inspection of the lactate concentration accumulated in human perspiration.

A more optimized idea is to build the functional components of the system based on the TENG model and, at the same time, exploit additional TENG units to collect and provide the energy required for the system processing circuits and wireless transmission. This design strategy will further reduce the system power consumption and even make the system completely self-driving. In this regard, Fig. 8C puts forward a wireless body sensor network (BSN) system for heart-rate monitoring via integration of a downy-structure-based TENG (D-TENG), a PM circuit, a TENG-based heart-rate sensor, a signal processing unit, and Bluetooth module for wireless data transmission [167]. By converting the inertia energy of human walking into electric power, the D-TENG delivers a maximum power of 2.28 mW with a total conversion efficiency of 57.9% at low operation frequency, which is capable of immediately and sustainably driving the BSN system.

Featuring self-powered, cost-effective, noninvasive, and user-friendly, TENG-powered systems flourish rapidly in recent years in many fields. In addition to the involvement in biomedical fields mentioned above, TENGs have stepped into daily life. Taking TENGs embedded in the mobile bracelets to capture energy from the swing arm and activate low-power digital displays/liquid crystal screens (LCDs) [54,55,168] as an example, more and more wearable technologies will be inseparable from TENGs.

4.2. Process-level integration

Secondly, since most of the current systems only meet the requirements of integration in terms of performance, it is particularly important to consider more factors to achieve a higher integration level. With respect to the processes of systems, assembling TENGs and energy-storage devices (micro-supercapacitors (MSCs), lithium ion battery (LIB), etc.) with compatible processes into self-charging power units (SCPU) [169–171] is an effective approach to improve the system integration and make them more compact and wearable.

In Fig. 8D, yarn MSCs are woven into the fabric TENG (F-TENG) to harvest and store energy and to power electronic devices [172]. Interestingly, the F-TENG tactfully takes advantage of the harmful and annoying electrostatic breakdown phenomenon of clothes to obtain direct current (DC). Due to the special working mechanism, such a F-TENG harvests human motion energy and directly stores it in MSCs without any rectifier bridge or diode. In addition, since the manufacturing only incorporate weaving process, such electronic systems have no additional interconnection elements and are intrinsically wearable. Another stretchable coplanar SCPU textile with TENGs and MSCs both fabricated through a resist-dyeing-analogous method maintains excellent conductivity at 600% and 200% tensile strain along course and wale directions, respectively [173]. Thus, such an integration method suggests great wearable application prospect.

A portable, green and ultra-lightweight SCPU in Fig. 8E is capable of driving various miniaturized electronics such as a temperature/humidity indicator. The reason is that the SCPU consists a paper-based TENG (P-TENG) with high output power density and a paper-based MSC (P-MSC) with a great areal capacitance [174]. A cellulose paper/-polypyrrole composite with a low sheet resistance of 7.8 Ω sq^{-1} replaces the conventional metal electrodes and positive friction material in the P-TENG, as well as the capacitive material in the P-MSC.

The deformation such as stretching can lead to deterioration of electrical performances of most conductive nanomaterials [75]. To address these issues, Fig. 8F presents a SCPU all based on stretchable laterally combed CNT networks [175]. Additional nickel electroplating and serpentine electrode designs further increase conductivity and deformability. Such characteristics in addition to intrinsic electrochemically active property of CNTs enable high performance stretchable energy harvesting (wireless charging coil and TENG) and storage (LIB and MSC) devices. Monolithic integration of these devices forms a wearable SCPS, successfully demonstrating its potential as a novel soft power supply module for wearable electronics.

For addressing the energy bottleneck of wearable/portable smart devices, the further compatibility of SCPU with the driven electronic devices and associated circuit modules deserve further exploration [176–178]. Another counterpart to improve system integration is to simplify and optimize the system configuration, which appears in the following references [179–183].

In general, numerous self-powered systems have adopted the TENG as a power source to further explore its versatile applications toward different targets (more details of such systems can be found in Table 3). While focusing on the energy efficiency of TENGs, the energy consumption of other modules, the energy transfer between modules, and the interconnection and wearability of the whole system also demand further comprehensive design. Besides, the contradiction between the miniaturization of the system to increase its portability and the positive correlation between TENG's output and area also requires us to weigh and consider.

5. Summary and perspective

In summary, this review begins with the specific wearable structures/forms of TENGs and the underlying basic principles. Several promising materials and fabrication techniques appear subsequently, providing a foothold for the preparation for wearable TENGs. With an optimized design, wearable TENGs can play a key role in active sensors, actuators and smart human-machine interfaces, with large amount of available information behind the TENGs' signals. In addition, TENGs can serve as a stable power supply to continuously power other electronic systems without consuming excess resources. Furthermore, TENGs have made great progress both in performance-level integration and process-level integration amid the development of the wearable electronics.

Although TENGs have exhibited unique and multifunctional features, several challenges still lie ahead (Fig. 9):

- For the selection of materials and processes, when considering practical performance (portability, conformality, biocompatibility, breathability, washability, self-healing capacity, wide operating temperature, etc.), we could not ignore the concession of material electrical properties and process cost. Detailedly, the portability of TENGs requires materials with better flexibility/stretchability [184], light weight [185,186], and even shape-adaptability/memory [187]; Combining with the biocompatibility emphasized in the "materials and processes" section, an ultrathin configuration can conformally attach on human skin to act as a highly sensitive sensor [188,189]; When embedding TENGs into daily clothing for wearable applications, under the premise of ensuring performance and cost, the original breathability [190], and washability [191–193] of the clothing should not be affected; In addition to coat TENGs with antiwear and healing materials [194], if the materials of electrification layers and electrodes show intrinsic self-healing feature, the outputs of the TENGs can almost restore their original state when the damage of the devices occurs [37,195,196]; Under extreme outdoor weather conditions, the matrix/solvent of the TENGs should not undergo phase change to ensure stable mechanical and electrical

Table 3
Comparison of wearable TENG-based systems.

Components	Materials & processes	Configurations	Performance	Wearability	Reference
TENG, biosensors & flexible circuitry	FPCB-based TENG & circuitry, laser-cutting for sensor array	Horizontal arrangement	TENG's output power of 416 mW/m^2; powering multiplexed sweat sensors and wirelessly transmitting data to user	worn on the side torso	[165]
TENG, capacitor & lactate sensor	Soft lithography for TENG	Interconnection with wires	TENG's output power of 2.5 W/m^2; real-time lactate detection in human perspiration	assembled on the insole	[166]
TENG & power management, TENG-based sensor & signal management	Laser-cutting & plasma treatment for TENG	Horizontal arrangement	TENG's output power of 2.28 mW; real-time heart-rate monitoring	assembled on the arm	[167]
TENGs, EMGs & MSCs	All tube-based process	Sleeve structure	Self-charging to 2 V with a single wrist shake; powering most electronic devices for minutes	worn on the arm	[168]
TENG & MSC	All fabric based process	woven structure	DC output of TENG; lighting 416 LEDs or low-power LCD @1.5 cm × 3.5 cm area	Similar to commercial fabrics	[172]
TENGs & MSCs	All resist-dyeing-analogous process	woven structure	TENG's output power of 94.5 mW/m^2; powering the small electronics intermittently	Similar to commercial fabrics	[173]
TENG & MSC	All paper-based process	Horizontal arrangement	TENG's output power of 0.83 W/m^2; driving various miniaturized electronics	worn on the arm	[174]
TENGs, MSCs, LIB & coil	All CNT-PDMS-elastomer based process	Serpentine stretchable interconnection	Enduring 100% stretching; wireless energy transmission	skin-attachable	[175]
TENG, PENG & MSCs	All laminating based process	Vertical stacking	Self-charging to 3 V to light up LEDs; Visualized charging process	worn on the body	[179]
TENG & MSCs	All carbon-silicone based process	Vertical stacking	TENG's charge density of 97 μC/m^2; Enduring 100% stretching	worn on the body	[182]
TENG & MSC	All cut-paper-based process	Kirigami structure	TENG's charge density of 75 μC/m^2; charging MSC (~ 1 mF) to 1 V in minutes	assembled into the wallet	[183]
TENG, temperature sensor & flexible circuitry	Spray-coating process for TENG and sensor array	Horizontal arrangement	Charging a 100 μF capacitor to 1 V in 105 s; driving the sensor continuously more than 100 s	skin-attachable	[207]

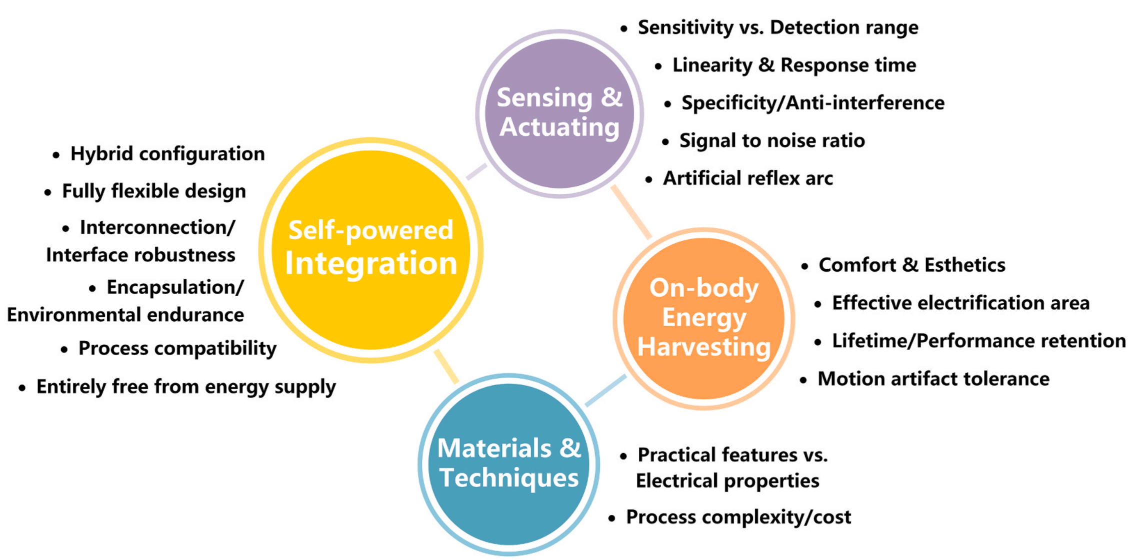

Fig. 9. Challenges and prospects of wearable TENGs.

performance [70,83]; The matching processes of these practical materials should be developed, and the process complexity, efficiency and cost should be optimized.

- For actual on-body energy harvesting, comfort and esthetics are the top considerations for the public, which contradicts with effective electrification area/efficiency per unit area. In addition to the sports protective gear and accessories forms of TENGs mainly with satisfying sensitivity/accuracy for active devices, the configurations in the forms of fabric, textile, and insoles with higher energy conversion efficiency also deserves our attentions. Taking the application of insoles as an example, learning from the design of commercial products can guide TENGs to be more invisibly merged into smart shoes while ensuring TENGs' effective operation [197,198]. Besides, we can enrich and expand the concept of "Wearable", that is, make TENGs incorporate comfort and efficiency through indirect wearable forms, such as assembling TENG on the shoulder strap of the backpack to avoid direct contact between the body and device during energy harvesting [199]; or integrating TENGs into keyboards [200,201], screens [202] to collect energy from fingers since electronic devices have become mobile and portable. Meanwhile, long-term durability and motion artifact tolerance are two major elements when wearable TENGs go towards market, thereby the structural designs resistant to the human environment and extreme impacts become particularly critical.
- For active sensing, actuating and interaction, in addition to ensuring the basic features (sensitivity, detection range, linearity, response time, etc.) of devices, more attentions should focus on the specificity of sensing to avoid interference from redundant variables. The high-

quality signal with low noise in real situation can reduce the circuit difficulty of precise control and avoid unnecessary misoperation. When combined with neuromorphic devices and machine learning, wearable TENGs, as an ideal input terminal, should cooperate with back-end devices to realize the full function of artificial reflex arc.

- System-oriented design yields more challenges. Synthesizing with more types of energy harvesting methods can capture more forms of ambient energy to maintain the energy supply for the system [163, 203–206]. After absorbing multiple functional components, a fully flexible [165,207,208] even biocompatible [209–211] design of the system is necessary to meet the needs of wearability. The robustness of the interconnection among the modules is a prerequisite for long-term and reliable system operation. Under the premise of not significantly sacrificing system performance, effective encapsulation could endow the system with weatherability and especially resist the erosion of sensitive components by sweat [118,212]. The direct impact of the force required by TENG's friction electrification on other components should also be avoided. Besides, the fabrication process of each module should be as compatible as possible in order to achieve mass production. Finally, combined efforts in reducing the module power consumption, optimizing the PM circuit [213–216] to maximize the system energy transfer efficiency, and adopting self-driven PM [217] represents a future direction in building systems that can entirely get rid of the demand for external energy.

CRediT authorship contribution statement

Haixia Zhang: Supervision. **Haixia Zhang** and **Haobin Wang**: Conceptualization. **Haobin Wang** and **Haixia Zhang**: Visualization. **Haobin Wang**: Writing-Original Draft. **Haobin Wang, Mengdi Han, Yu Song,** and **Haixia Zhang**: Writing-Review & Editing. **Haixia Zhang**: Funding Acquisition.

Declaration of Competing Interest

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

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