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Progress of Advanced Devices and Internet of Things Systems as Enabling Technologies for Smart Homes and Health Care

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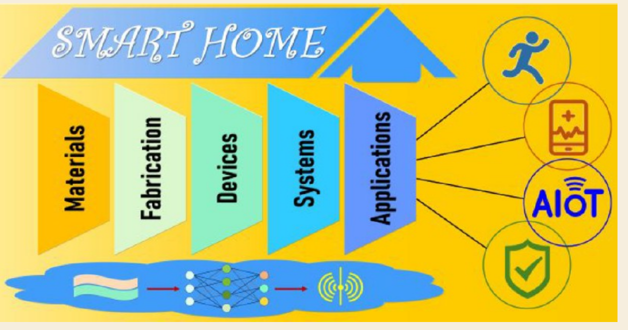
ABSTRACT: In the Internet of Things (IoT) era, various devices (*e.g.*, sensors, actuators, energy harvesters, *etc.*) and systems have been developed toward the realization of smart homes/buildings and personal health care. These advanced devices can be categorized into ambient devices and wearable devices based on their usage scenarios, to enable motion tracking, health monitoring, daily care, home automation, fall detection, intelligent interaction, assistance, living convenience, and security in smart homes. With the rapidly increasing number of such advanced devices and IoT systems, achieving fully self-sustained and multimodal intelligent systems is becoming more and more important to realize a sustainable and all-in-one smart home platform. Hence, in this Review, we systematically present the recent progress of the development of advanced materials, fabrication techniques, devices, and systems for enabling smart home and health care applications. First, advanced polymer, fiber, and fabric materials as well as their respective fabrication techniques for large-scale manufacturing are discussed. After that, functional devices classified into ambient devices (at home ambiance such as door, floor, table, chair, bed, toilet, window, wall, *etc.*) and wearable devices (on body parts such as finger, wrist, arm, throat, face, back, *etc.*) are presented for diverse monitoring and auxiliary applications. Next, the current developments of self-sustained systems and intelligent systems are reviewed in detail, indicating two promising research directions in this field. Last, conclusions and outlook pinpointed on the existing challenges and opportunities are provided for the research community to consider.



KEYWORDS: *smart home, sensor, system, energy harvesting, IoT, AI*

1. INTRODUCTION

With the significant advancement of 5G and Internet of Things (IoT) technologies, diversified IoT devices and wearable electronics have been developed in the past few years, targeted for a large variety of applications in environmental monitoring, motion tracking, human-machine interaction, health care, big data, intelligent sport, smart home, smart traffic, smart farming, and smart industry, *etc.*[1−13] Among them, smart home and health care are gaining enormous interests from research aspects to commercialization because of increased demands in terms of 5G/IoT connectivity, living amenity and safety, home healthcare, and automation. To realize smart homes, various functional devices, technologies, and systems based on advanced materials and fabrication techniques have been developed (Figure 1).[14−22] On the one hand, wearable electronic devices have been extensively explored to improve user experiences and personalized functionalities that could be seamlessly integrated on our skin or clothes, such as the electronic-skin (e-skin), e-textile, and body area monitoring network.[5,23−26] Besides the electronic devices, wearable photonic devices with particular advantages in user interfacing, signal output format, data communication rate, and integration capability have also been investigated.[27,28] Based on these wearable electronic and photonic devices, a more diversified and complementary wearable network and self-sustained sensing systems are realized.[29,30] On the other hand, various IoT sensors and systems have also been implemented in our living environments, to enable more generic monitoring and response functionalities, *e.g.*, home automation, health monitoring, daily care, fall detection, elderly assistance, rehabilitation, intelligent interaction, security, *etc.*[31−43]

Under the IoT framework, these widely deployed wearable devices and ambient devices could be linked up, with mutual communications among each other and the cloud server, thereby forming the basic building blocks of an interconnected

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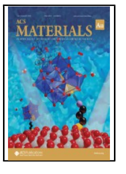

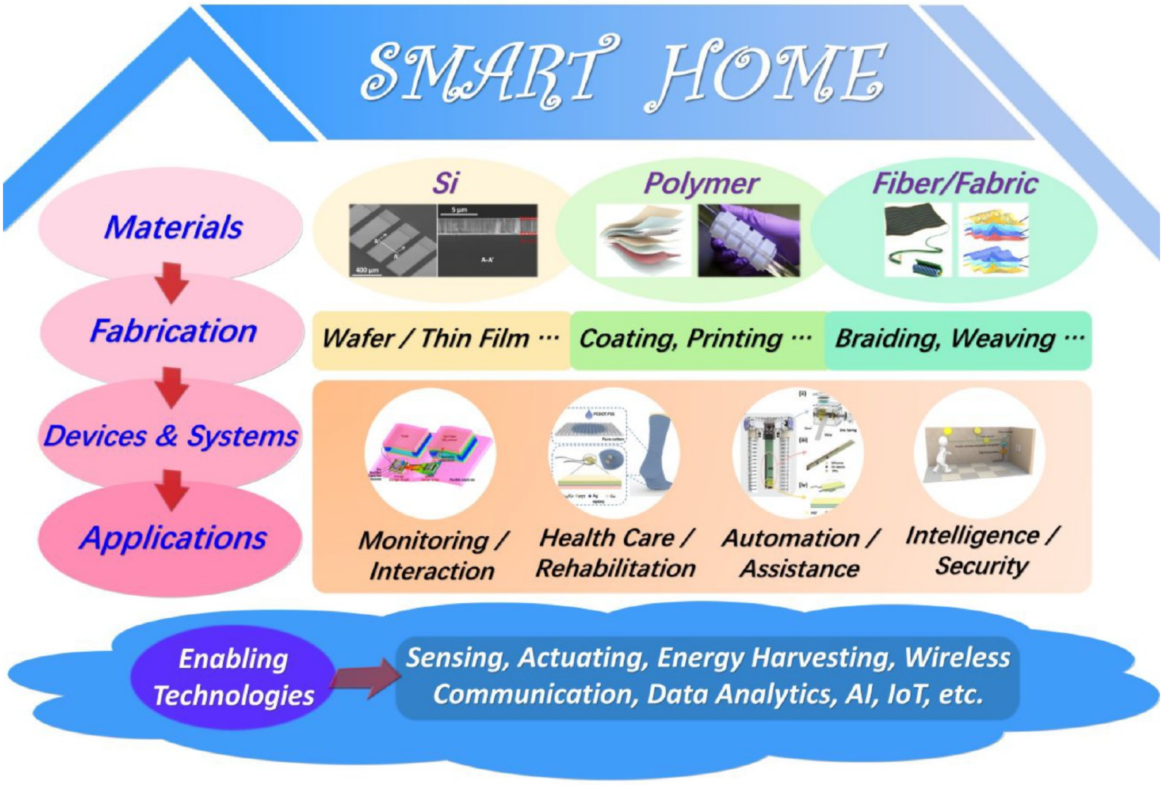

Figure 1. Overview of the development of materials, fabrication, devices and systems, applications, and the enabling technologies for smart homes and health care. Reprinted with permission under a Creative Commons CC BY License from ref 14. Copyright 2016 The Authors. Reproduced from ref 15. Copyright 2021 American Chemical Society. Reproduced with permission from ref 16. Copyright 2018 Elsevier. Reproduced with permission from ref 17. Copyright 2020 Elsevier. Reprinted with permission under a Creative Commons CC BY License from ref 18. Copyright 2019 The Authors. Reproduced with permission from ref 19. Copyright 2019 Elsevier. Reproduced from ref 20. Copyright 2019 American Chemical Society. Reproduced with permission under a Creative Commons CC-BY license from ref 21. Copyright 2021 The Authors. Reprinted with permission under a Creative Commons CC BY License from ref 22. Copyright 2020 The Authors.

smart home platform. In this way, the multimodal sensory information and user preferences can be shared within the smart home platform, to achieve better functionalities in varying conditions and different usage scenarios. With rapidly increasing devices and systems in smart homes, energy supply becomes a huge concern and the bottleneck for further development, due to the limited lifespan of the batteries as well as the nontrivial effort, time, and cost needed for their replacement. In this regard, self-sustained devices and systems that can operate independently without external power supplies are highly promising and desirable. Energy harvesters are the key enabler for such self-sustained systems, since they can scavenge the ambient available energy and convert it into electricity as the power source.[44−50] Differentiated by the transducing mechanisms, energy harvesters can be classified into different types, *e.g.*, photovoltaic or solar cell based on the photovoltaic effect,[51] thermoelectric generator (TEG) based on the Seebeck effect,[52−54] pyroelectric nanogenerator (PyENG) based on the pyroelectric effect,[55,56] electromagnetic generator (EMG) based on the electromagnetic induction,[57−59] piezoelectric nanogenerator (PENG) based on the piezoelectric effect,[60−64] triboelectric nanogenerator (TENG) based on the contact electrification and electrostatic induction,[65−72] *etc.* Since its first invention in 2012,[73] TENG has been vastly investigated and proven as a highly promising energy harvesting technology for ubiquitous mechanical energy harvesting (human activities, vibration, wave, wind, rain, *etc.*),[74−78] due to its great merits of high performance, low cost, ultrawide material availability, simple structure, great scalability, and high compatibility. By properly selecting the triboelectric materials from the more and more complete triboelectric series,[79,80] TENGs can be configured into four working modes, *i.e.*, vertical contact-separation mode, lateral sliding mode, single-electrode mode, and freestanding triboelectric layer mode.[81] Besides serving as energy harvesters, the energy harvesting devices can also function as self-powered sensors, since the self-generated signals are affected by the ambient parameters, such as pressure,[82] position,[83] vibration amplitude,[84] frequency,[85] wind speed,[86,87] *etc.* These self-powered sensors can operate actively without external energy supplements, which can effectively lower the overall power consumption of a system especially for continuous operation.

Except for the envisioned self-sustainability using energy harvesting, another key desired feature for the smart home systems is a higher level of intelligence, that can make optimal decisions and respond to various scenarios. In recent years, the significant development of artificial intelligence (AI) technologies has promoted the emergence of a wide range of intelligent sensors and systems with advanced data analytics assisted by machine learning (ML) or deep learning (DL),[88,89] *e.g.*, a gesture-recognition glove using visual and somatosensory data fusion,[90] a smart motion-capture device for recognizing dynamic limb motions,[91] an intelligent glove with object recognition and haptic feedback capability,[92] *etc.* Moreover, the technology fusion of AI and IoT has nurtured a new research field, *i.e.*, artificial intelligence of things (AIoT), with enhanced

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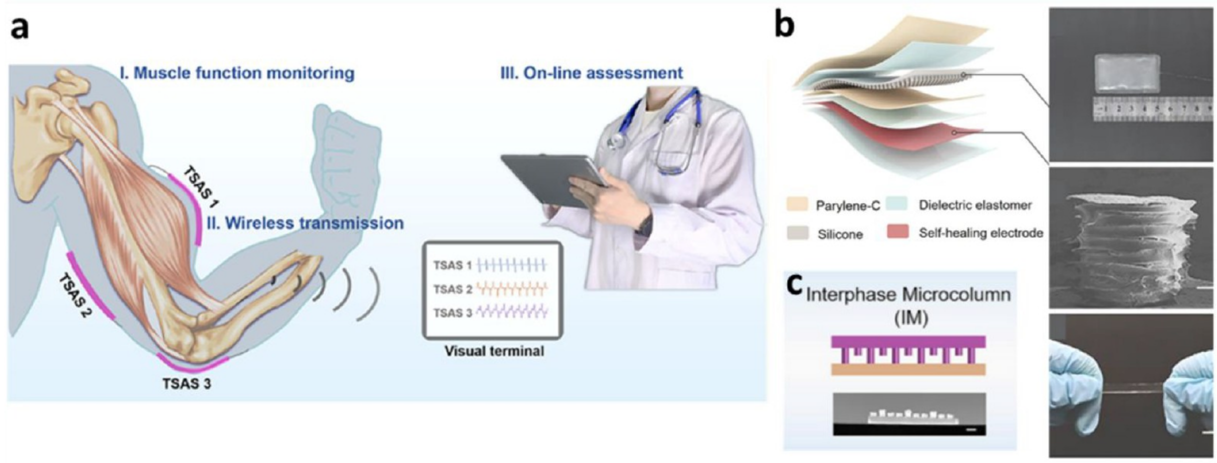

Figure 2. Advanced materials for e-skin wearable electronics. (a) Stretchable, self-healing, and skin-mounted active sensor for multipoint function assessment. (b) Schematic illustration of the sensor, including the components, assembly, and stretchability. (c) Schematic illustration of the interphase microcolumn for the triboelectric layer. Reproduced from ref 15. Copyright 2021 American Chemical Society.

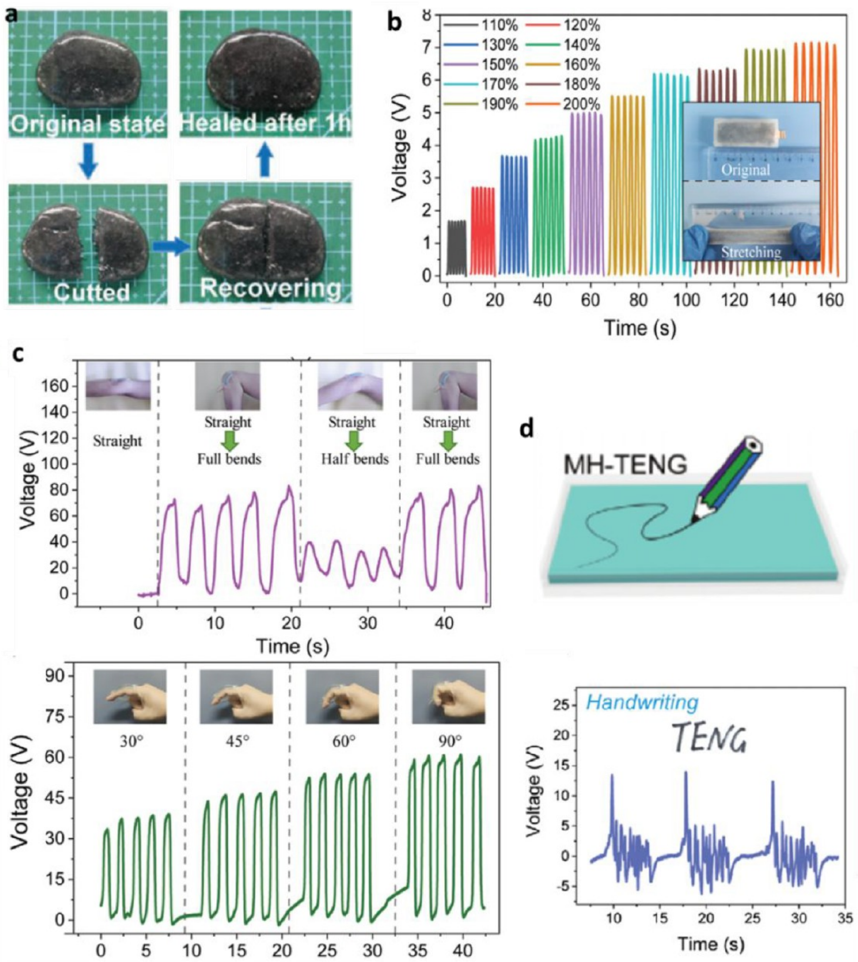

Figure 3. Advanced materials for e-skin wearable electronics. (a) Self-healing TENG based on MXene/PVA hydrogel. (b) Output performance of the TENG under different strain levels. (c) Application of the device for leg and finger bending monitoring. (d) Application of the device for written stroke recognition. Reproduced with permission from ref 110. Copyright 2021 John Wiley and Sons.

intelligence of IoT systems for smart applications.[93−96] In particular, several AIoT systems have been applied in wearable and home ambient electronics, for enabling personalized monitoring and healthcare, object recognition, gait analysis, individual identification, and security.[21,22,97] These AIoT system enabled smart homes and smart buildings exhibit not only multimodality monitoring and interactive functions, but also high intelligence and decision-making capability.

In this Review, we summarize the recent progress of various advanced devices and IoT systems for enabling smart homes

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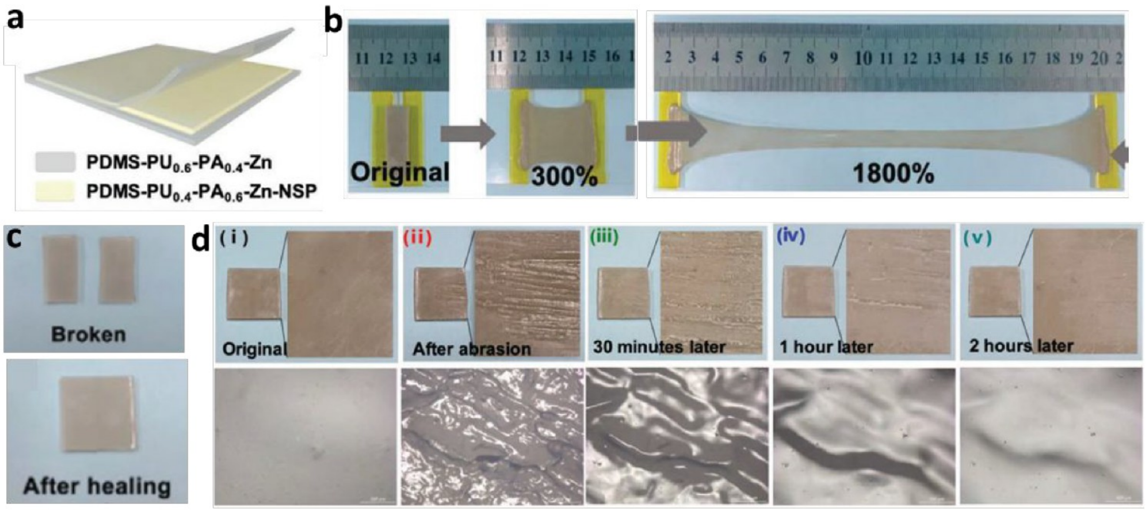

Figure 4. Advanced materials for e-skin wearable electronics. (a) Schematic illustration of the fabricated TENG device. (b) Illustration of the stretchability of the TENG device (1800% strain). Demonstration of the self-healing TENG that can repair a (c) fracture and (d) abrasion simultaneously. Reproduced with permission from ref 118. Copyright 2021 John Wiley and Sons.

and health care in the 5G and IoT era (Figure 1). First, advanced materials and fabrication techniques to realize functional and application-specific devices in smart homes are discussed. Next, ambient devices and wearable devices deployed in home environments and on human bodies are specified, with particular interests in the self-powered devices due to their predominant advantages to enable low power consumption and even self-sustainability. Here, the self-powered devices refer to those devices that can self-generate varying electrical output signals corresponding to an external stimulus such as contact, pressure, acceleration, light, or heat, based on the energy transducing mechanism of piezoelectric effect, triboelectrification coupled electrostatic induction, photovoltaic effect, or thermoelectric effect. Afterward, the current technology developments of self-sustained systems and intelligent systems are reviewed in detail, indicating the two promising development trends in smart homes. In the end, conclusions and outlook are provided to emphasize the existing challenges and opportunities for the future development of all-in-one, fully connected, and AI-enabled smart home platforms.

2. ADVANCED FUNCTIONAL MATERIALS

One important trend in developing sensors for IoT and smart home applications is toward higher wearability using advanced materials and structures.[9,29,98] Wearable sensors can be mainly divided into two categories: e-skin sensors[99−101] and textile sensors.[102−104] The e-skin sensors aim to perform their functions when attached to human skin, while textile sensors are woven into our daily clothes to achieve sensing purposes. Both of them are required to be compatible with human health and to withstand frequent body motions. Hence, flexibility, breathability, washability, and durability are all key properties for the investigation of wearable sensors. In this section, we will introduce some functional materials that help to realize the required properties for wearable sensors, including stretchable, self-healing, and hydrophobic materials. Meanwhile, 2D materials that help with the performance enhancement will be covered as well.

Regarding e-skin electronics, Wang *et al.* reported a skin-mounted active sensor for multipoint muscle function assessment, as shown in Figure 2.[15] This triboelectric sensor uses silicone rubber and parylene as the triboelectric materials and an ionic hydrogel as the electrode material. Silicone rubber is extensively employed in TENGs because of its structure designability, high performance, and flexibility.[105−107] Here, silicone rubber is designed with interphase microcolumns which can help to increase the outputs of TENGs. The ionic electrode is endowed with large deformation tolerance and fast self-healing capability due to polymer segment entanglement and dynamic hydrogen bonds. It takes ∼30 min for the completion of the self-healing process for a fractured ionic hydrogel at room temperature. The stretchability of this ionic hydrogel is over 2000% even after one self-healing process. With three sensors attached to the biceps, triceps brachii, and elbow, respectively, the generated output signals are acquired simultaneously and transmitted wirelessly for analysis. Thus, real-time and quantitative monitoring of muscle strength and joint curvature can be realized for further medical assessment.

Moreover, 2D materials have been introduced into the preparation of TENGs owing to their unique properties of metal conductivity, high specific surface areas, and good mechanical strength.[108,109] Luo *et al.* reported a multifunctional TENG based on the MXene/polyvinyl alcohol (PVA) hydrogel in Figure 3.[110] Compared with the pure PVA hydrogel, the doping of MXene nanosheets promotes the cross-linking of the PVA hydrogel to improve the stretchability up to 1800%. Furthermore, the self-healing property is enhanced due to the additional hydrogen bonds provided by the abundant surface functional groups from MXene. Meanwhile, with the microchannels formed by MXene nanosheets, the conductivity of the hydrogel has been enhanced by improving the transport of ions. In addition, extra triboelectric output is generated *via* a streaming vibration potential (SVP) mechanism, which is attributed to the formation of an electrical double layer (EDL) between MXene nanosheets and water in the 3D porous structure of MXene-PVA hydrogel. The pressure-driven flow can drag extra electrons in the EDL to move back and forth, generating the electric current (streaming current) and the SVP for output enhancement. When the MXene/PVA hydrogel is encapsulated between Ecoflex, a stretchable and self-healing TENG is fabricated. By utilizing the device's outstanding stretchable property and

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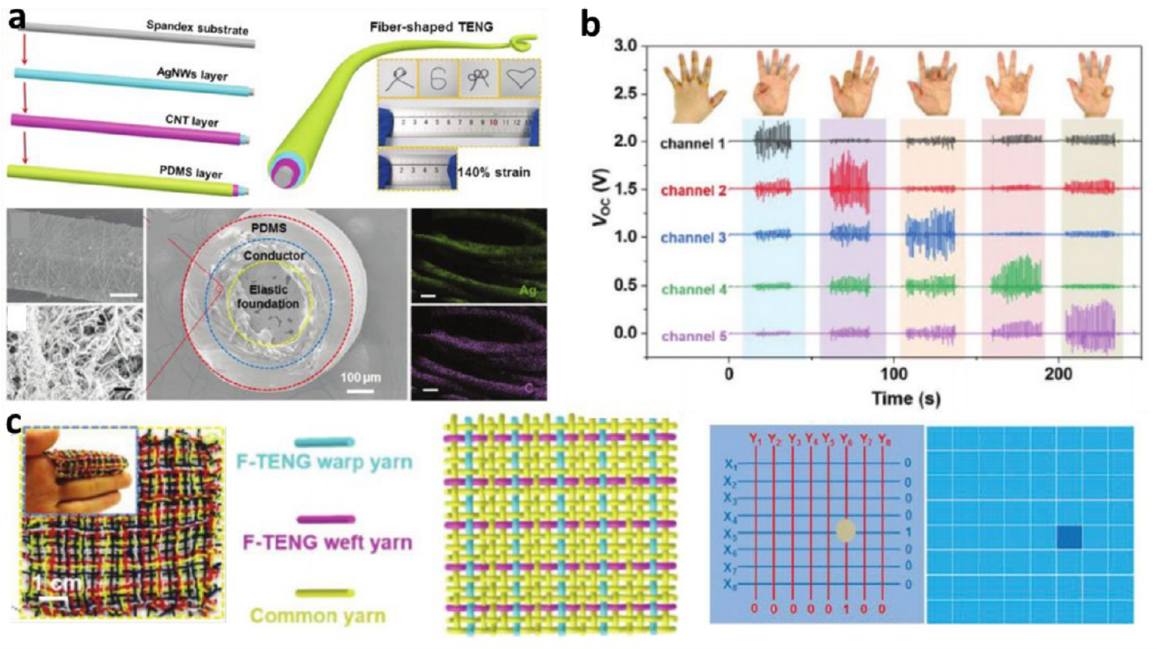

Figure 5. Advanced materials for textile-based wearable electronics. (a) Fabrication process and structural illustration of the flexible and stretchable fiber-based TENG. (b) Application of the fiber TENG for gesture recognition. (c) Knitting structure of the fabric as a tactile sensor with 8 × 8 pixels. Reproduced with permission from ref 119. Copyright 2020 John Wiley and Sons.

ultrahigh sensitivity to mechanical stimuli, applications of finger bending monitoring and high-precision written stroke recognition are demonstrated successfully.

Besides the self-healing electrodes, many efforts have also been spread to the investigation of triboelectric materials.[111−116] Lai *et al.* fabricated a whole self-healing TENG device using a healable, transparent, and stretchable polydimethylsiloxane (PDMS) as the triboelectric layer and hydrogel as the electrode.[117] The above works mainly focus on repairing fractures of devices, while another important type of damage, *i.e.*, abrasion that is unavoidable and significant in triboelectric devices due to the continuous contact or friction between two triboelectric materials, is rarely investigated. To address this issue, Jiang *et al.* reported an abrasion-healable hydrogel by introducing hydrogen bonds and dynamic metal−ligand coordination into the PDMS networks (Figure 4).[118] Fracture and abrasion in this hydrogel can be simultaneously repaired at room temperature. The TENG is fabricated by sandwiching the self-healable PDMS-PU-PA-Zn-NSP electrode between two self-healable PDMS-PU-PA-Zn triboelectric films. Thus, the whole TENG device not only is healable for fractures and abrasions but also possesses ultrahigh stretchability of about 1800%. If the TENG is stretched to break or wear out, the triboelectric outputs can recover at room temperature in about 20 min and 2 h, respectively.

Speaking of the textile-based TENGs, improved wearability is investigated regarding the single fiber and the textile itself. As shown in Figure 5, Ning *et al.* reported a stretchable fiber-shaped TENG.[119] It is fabricated by depositing Ag nanowires (NWs) onto a stretchable Spandex fiber substrate, followed by dip coating with carbon nanotubes (CNTs) for better conductivity and stability. Finally, the fiber is encapsulated by PDMS to form the coaxial structure. Such a fiber-based TENG has good flexibility and stretchability, allowing it to be folded into different shapes and stretched up to 140%. The fibers are fixed on human fingers for physiological monitoring where the triboelectric outputs vary from different bending angles; thus, different gestures can be monitored and recognized through the five output channels. Meanwhile, the fibers are woven into cloth to form an 8 × 8 tactile sensor array including 8 warp yarns and 8 weft yarns. When the sensor array is touched, the corresponding pixels will generate signals which will be transmitted to the data analysis terminal for real-time display. In Figure 6, Lai *et al.* also reported a fiber-shaped device by filling metallic EGaIn liquid into an elastic poly(styrene-*b*-(ethylene-co-butylene)-*b*-styrene) (SEBS) hollow fiber.[120] This fiber shows higher stretchability (over 400%) than the previous one (140%), since EGaIn liquid possesses a much lower Young's modulus than those of the Ag NWs and CNTs. Thus, in order to improve the stretchability of devices, materials with lower Young's Modulus are relatively better candidates. The EGaIn fiber can be used for harvesting not only mechanical energy from body motion but also electromagnetic energy from surrounding electrical appliances. In addition, the fibers are woven into gloves as self-powered finger-motion sensors depending on the distinguishable outputs from different bending angles. Since the electrical outputs from static and transient touch are different, the fibers on the glove can also be used as a human-interactive platform for Morse code transmission. A self-powered gesture sensing glove is also demonstrated by weaving five separate fibers into the glove. Similarly, the fibers are woven into cloth as an active human−system interface to dial phone numbers and control music with the help of a microcontroller.

On top of the research effort on fibers, Xiong *et al.* reported a washable skin-touch actuated textile-based TENG using black phosphorus (BP) for durable biomechanical energy harvesting, as indicated in Figure 7.[121] The BP and cellulose-derived hydrophobic nanoparticles (HCOENPs) are successively coated on a polyethylene terephthalate (PET) fabric as the triboelectric layer. Ag flakes and PDMS are then coated on a second PET fabric as the electrode layer. Another

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Figure 6. Advanced materials for textile-based wearable electronics. (a) Fabrication of liquid-metal fiber based TENG for energy harvesting and self-powered sensing. (b) Illustration of the ultrastretchability of the fiber. (c) Application of the fiber as a self-powered human-interactive fiber and gesture glove. (d) Application of the fiber as a wearable keypad and music controller. Reproduced with permission from ref 120. Copyright 2021 John Wiley and Sons.

HCOENPs coated PET fabric is used to encapsulate the whole structure to form the waterproof textile-TENG. The device can be folded, twisted, and even stretched to 100%. The triboelectric output of this device (HCOENPs/BP/PET fabric) is greatly enhanced compared to the pure PET fabric, BP/PET fabric, and HCOENPs/PET fabric, because of the synergistic effects that the BP acts as an electron-accepter layer and HCOENPs help to reduce the influence of water. Overall, these investigations of functional materials show great potential as sensor materials with improved wearability. A summary table of wearable TENGs regarding e-skin and textile-based devices is provided in Table 1, and their corresponding properties are also listed including the materials, fabrication techniques, output performance, stretchability, self-healing capability, self-adhesiveness, as well as applications.

3. SCALABLE FABRICATION TECHNOLOGIES FOR LARGE-AREA APPLICATIONS

Despite the advancements in materials, the fabrication techniques of IoT sensors are also moving toward large-scale industrialized production, which is prominent for commercial and widespread applications.[143−146] Here we will introduce several large-scale fabrication techniques for flexible devices, including thin-film-based devices and textile-based devices. As shown in Figure 8, a simple spray-coating process is employed to deposit the silk-fibroin (SF) as a triboelectric layer on a PET/indium tin oxide (ITO) substrate.[147] First, the SF powders are dissolved in deionized water. The as-prepared solution is then loaded into an airbrush-style spray gun and subsequently sprayed onto a PET/ITO film with a thickness of 125 μm. Finally, a large-scale sheet with the dimension of 36 × 36 cm^2 is obtained and can be cut into smaller pieces for TENG construction. An arch-shaped TENG is fabricated from

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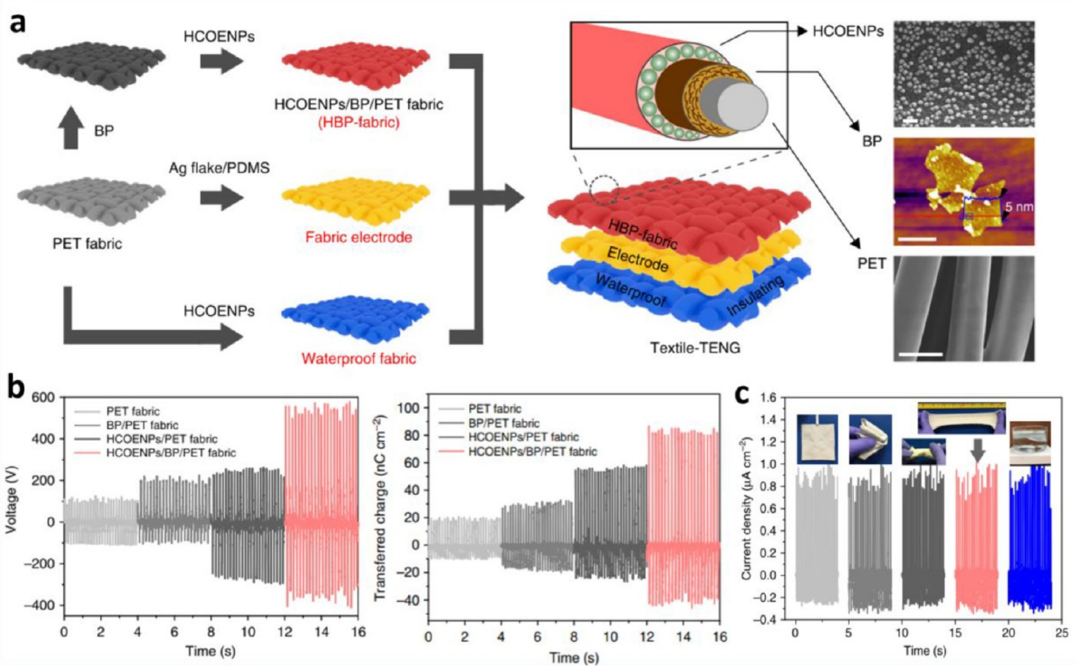

Figure 7. Advanced materials for textile-based wearable electronics. (a) Fabrication process and structural illustration of the textile-based TENG. (b) Output performance enhancement of the TENG with black phosphorus and hydrophobic coating. (c) Output performance under different deformations and severe washing. Reprinted with permission under a Creative Commons CC BY License from ref 121. Copyright 2018 The Authors.

two sheets: one is the SF/PET/ITO sheet, and the other is the PET/ITO sheet. The as-fabricated TENG exhibits a maximum voltage of 213.9 V and a high power density of 68.0 mW/m^2.

Surface modification of triboelectric materials is an effective strategy to enlarge the contact area so as to enhance the output of TENGs.[148−150] Soft lithography, plasma etching, and chemical treatment are the general methods to improve surface topography.[151−153] However, they are relatively expensive, nonscalable, and limited by the wafer or chamber size of the fabrication tools. As shown in Figure 9, Dhakar *et al.* reported a low-cost roll-to-roll ultraviolet (UV) embossing to pattern PET sheets as the triboelectric layer without any length restrictions of the film.[154] The setup of the roll-to-roll UV embossing system consists of four modules: (1) unwinding module for supporting PET substrate, (2) coating module for depositing UV curable resin on PET film, (3) UV embossing module for patterning microstructures on PET film, and (4) rewinding module that provides web tension for separating the embossed PET film from the embossing roller and then rewinds for collecting the embossed PET film. A lamination technique is used to fabricate the large-scale copper film on top of liquid crystal polymer (LCP) as an electrode layer and another triboelectric layer. The obtained TENG can be used to harvest energy from human motions and vehicle motions by embedding devices in floors and roads, respectively. In the meantime, the roll-to-roll technique is also employed to form pixel patterns on PET films for pressure sensing. For the corresponding electrode of each pixel, commercially available stock paper is used as a substrate to make electrode patterns for individual pixels using aluminum foil. The fabricated 7 × 3 sensor array exhibits a pressure detection sensitivity of 1.33 V/kPa, and it is assembled on the back of a chair for posture monitoring when a person sits on the chair.

In addition to the large-scale fabrication of triboelectric layer, Shi *et al.* utilized a highly scalable screen-printing technique to print a silver paste electrode on PET substrates as large-area triboelectric floor mats (Figure 10).[22] Six unique electrode patterns are screen-printed on the PET film with varying electrode areas so that the triboelectric outputs from them are distinguishable when a user walks on the floor mats. With a parallel connection of six mats, only one electrode is created for signal readout, which simplifies the data analysis and lowers the power consumption. Stepping positions and activity status can be monitored successfully through the floor mats by analyzing the output magnitudes. Meanwhile, the authors have also integrated the floor mat with deep learning analysis for identity recognition. The walking gait patterns of each individual can be extracted from the output signals through a convolutional neural network (CNN) model. This developed smart floor technology demonstrates an excellent example of using floor sensors toward smart buildings and smart homes, *e.g.*, indoor positioning, intelligent control, healthcare, and security.

Regarding the large-scale fabrication technique for textile-based sensors, Wang *et al.* reported a convenient method to achieve a liquid metal/polymer core/shell fiber (LCF) structure by simply pumping liquid metal into ultrafine polymer hollow fibers, as shown in Figure 11.[140] Based on these fibers, a breathable and soft TENG textile can be fabricated by using the traditional Chinese weaving machine. The textile TENG with an area of 6 × 8 cm^2 can generate a maximum V_{oc} (open-circuit voltage) of 206 V and I_{sc} (short-circuit current) of 28.7 μA by tapping it with a cotton glove. It should be mentioned that the pumping method is suitable for diverse choices of shell materials, contributing to robust and promising energy sources that can adapt to various environments. Moreover, as shown in Figure 12, Zhou *et al.* reported a

Table 1. Summary Table of Wearable E-Skin and Textile TENGs.

device type	triboelectric materials	electrode materials	structure	working mode	manufacture technology	scalability	size	output performance	stretchability	self-healing capability	adhesiveness	application	ref
e-skin	PDMS/nylon	TPU-AgNWs	thin film	single-electrode mode	electrospinning and electrospray	N.A.	2 × 2 cm^2	95 V, 0.3 μA	800%	N.A.	yes	self-powered haptic sensor	122
	PDMS	graphene	epidermal	single-electrode mode	transfer and coating	N.A.	NF	15 V, 5 μA @ finger touch	13.7%	N.A.	yes	self-powered tactile sensor array	123
	PDMS	Cu	epidermal	single-electrode mode	spin-coating, lithography, etch, transfer and printing	N.A.	75 × 75 mm^2	180 V, 2.2 μA	30%	N.A.	yes	energy harvester, self-powered HMI	124
	PDMS	Iongel	thin film	single-electrode mode	handmade	N.A.	2.5 × 2.5 cm^2	117 V, 14.3 μA, 47 nC	>400%	yes	N.A.	energy harvester, motion sensor	125
	silk nanofibers/PVA-MXene nanofibers	Al foil	thin film	contact separation mode	electrospinning	yes	1.8 cm diameter	118.4 V @ 10 Hz	NF	N.A.	N.A.	energy harvester, activity sensor	126
	VHB/nylon	ion-conducting elastomer	thin film	single-electrode mode	handmade	N.A.	3 × 3 cm^2	90 V, 30 nC, 1.25 μA	1036%	N.A.	N.A.	energy harvester, pressure sensor	127
	TPU	multilayered rGO-AgNWs	thin film	single-electrode mode	handmade	N.A.	2 × 2 cm^2	202.4 V	200%	N.A.	N.A.	energy harvester, tactile sensor	128
	PU/silicone rubber	gelatin-PAM and PEDOT:PSS hydrogel	thin film	single-electrode mode	handmade	N.A.	6 × 6 cm^2	383.8 V, 26.9 μA, 92 nC	300%	N.A.	N.A.	energy harvester	129
	silicone rubber	PO-WPU-PA composite	thin film	single-electrode mode	handmade	N.A.	NF	104 V, 8.0 μA, 34 nC	100%	N.A.	yes	energy harvester, tactile sensor	71
	graphite-PDMS composite/PDMS	ITO	thin film	contact separation mode	roll printing	yes	5 × 5 cm^2	410 V, 42 μA, 160 nC	N.A.	N.A.	N.A.	energy harvester, tactile sensor	130
	silicone rubber/Parylene-C	PVA-PEI-LiCl ionic hydrogel	bulk structure	single-electrode mode	handmade	N.A.	3 × 5 cm^2	78.44 V, 1.42 μA, 47.48 nC	66%	yes	yes	sensors for muscle function assessment	15
	silicone rubber	AgNWs	bulk structure	single-electrode mode	handmade	N.A.	2.5 × 2.5 cm^2	70 V, 100 $\mu C/m^2$, 6 mA/m^2 @ 4 Hz	300%	N.A.	N.A.	energy harvester	106
	PDMS-$PU_{0.6}PA_{0.4}$-Zn	PDMS-$PU_{0.6}PA_{0.4}$-Zn-NSP	bulk structure	single-electrode mode	handmade	N.A.	2 × 2 cm^2	140 V, 40 nC, 1.5 μA	1800%	yes	N.A.	energy harvester, pressure sensor	118
	Ecoflex/Kapton	MXene-PVA hydrogel	bulk structure	single-electrode mode	handmade	N.A.	2 × 5 cm^2	230 V	200%	yes	N.A.	body sensor, energy harvester	131
	VHB/nylon	PAAm-LiCl hydrogel	bulk structure	single-electrode mode	handmade	N.A.	3 × 4 cm^2	120 V, 1.7 μA, 47 nC @ 1.5 Hz	1160%	N.A.	N.A.	energy harvester	68
	silicone rubber/skin	Galinstan	bulk structure	single-electrode mode	handmade	N.A.	6 × 3 cm^2	354.5 V, 15.6 μA, 123.2 nC @ 3 Hz	300%	N.A.	N.A.	energy harvester	132
	silicone rubber/skin	potassium iodide and KI-Gly electrolyte	bulk structure	single-electrode mode	handmade	N.A.	4 × 4 cm^2	300 V, 28 μA	412%	N.A.	N.A.	energy harvester, self-powered HMI	133

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Table 1. continued

device type	triboelectric materials	electrode materials	structure	working mode	manufacture technology	scalability	size	output performance	stretchability	self-healing capability	adhesiveness	application	ref
	polyurethane acrylate (PUA)/latex	Ag flakes-liquid metal-PUA	bulk structure	single-electrode mode	handmade	N.A.	3 × 3 cm^2	100 V, 4 $\mu A/cm^2$, 12 nC/cm^2 @ 5 Hz	2500%	yes	N.A.	energy harvester	112
	silicone rubber/PTFE	liquid CNT-MXene	bulk structure	single-electrode mode	handmade	N.A.	8 × 4 cm^2	300 V, 5.5 μA, 120 nC	120%	N.A.	N.A.	energy harvester, motion sensor	134
	silicone rubber	PAM-HEC-LiCl hydrogel	bulk structure	single-electrode mode	handmade	N.A.	3 × 3 cm^2	285 V, 15.5 mA, and 90 nC @ 2.5 Hz	150%	yes	N.A.	energy harvester	135
textile	PDMS	AgNWs and CNT	fiber	single-electrode mode	handmade	N.A.	0.63 mm diameter	22 V, 0.6 μA, 7.5 nC @ 5 Hz	200%	N.A.	N.A.	self-powered physiological monitoring, tactile sensor	119
	SEBS	liquid EGaIn	fiber	single-electrode mode	melt extrusion	yes	1 mm diameter, 5 cm length	160 V/m, 60 nC/m	650%	N.A.	N.A.	energy harvester, finger sensor, HMI	120
	silicone rubber	NaCl solution	fiber	single-electrode mode	handmade	N.A.	12.7 mm diameter, 5 cm length	67.71 V, 0.83 mA/m^2, 35.35 mC/m^2	300%	N.A.	N.A.	energy harvester	136
	silicone rubber/cotton	PA yarn coated with Ag	textile	contact separation mode	double needle bed flat knitting	yes	25 cm^2	40 V, 100 nA, 13 nC	300%	N.A.	N.A.	energy harvester, 3D tactile sensor	137
	HBP fabric/Skin	Ag flake-PDMS-PET fabric	textile	single-electrode mode	handmade	N.A.	7 × 7 cm^2	860 V, 1.1 $\mu A/cm^2$ @ 6 Hz	N.A.	N.A.	N.A.	energy harvester	121
	silicone rubber	stainless steel/polyester fibers	textile	single-electrode mode	weft-knitting	N.A.	4 × 4 cm^2	150 V, 52 nC, 2.9 μA @ 5 Hz	60%	N.A.	N.A.	energy harvester	138
	PMA/PTFE	PNA hydrogel	textile	single-electrode mode	handmade	N.A.	4 × 2 cm^2	36 V, 0.5 μA, 10 nC @ 1.25 Hz	100%	N.A.	N.A.	energy harvester	139
	PTFE/cotton	liquid metal	textile	contact separation mode	pumping	yes	6 × 8 cm^2	206 V, 28.7 μA @ hand tapping	200%	N.A.	N.A.	energy harvester	140
	MXene-silicone/skin	Ag coated conductive fabric	textile	single-electrode mode	handmade	N.A.	2.5 × 2.5 cm^2	1.47 kV, 200 mA/m^2	N.A.	N.A.	N.A.	energy harvester	141
	PA66-MWCNTs NF/PVDF NF	conductive fabric	textile	contact separation mode	electrospinning	yes	2 × 2 cm^2	142 V, 15.5 μA	N.A.	N.A.	N.A.	energy harvester	142

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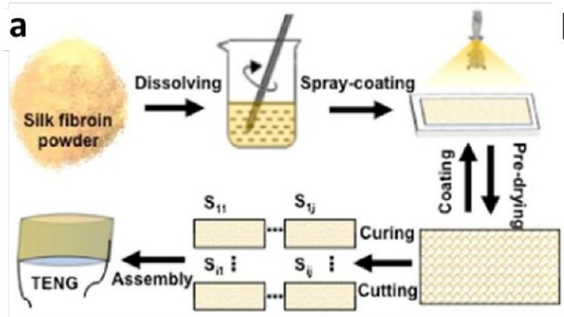

Figure 8. Scalable fabrication techniques to enable large-area applications. (a) Fabrication process of the large-scale TENG with the silk-fibroin patch film via a spray-coating process. (b) Photograph of the prepared large-scale and flexible film. Reproduced with permission from ref 147. Copyright 2017 Elsevier.

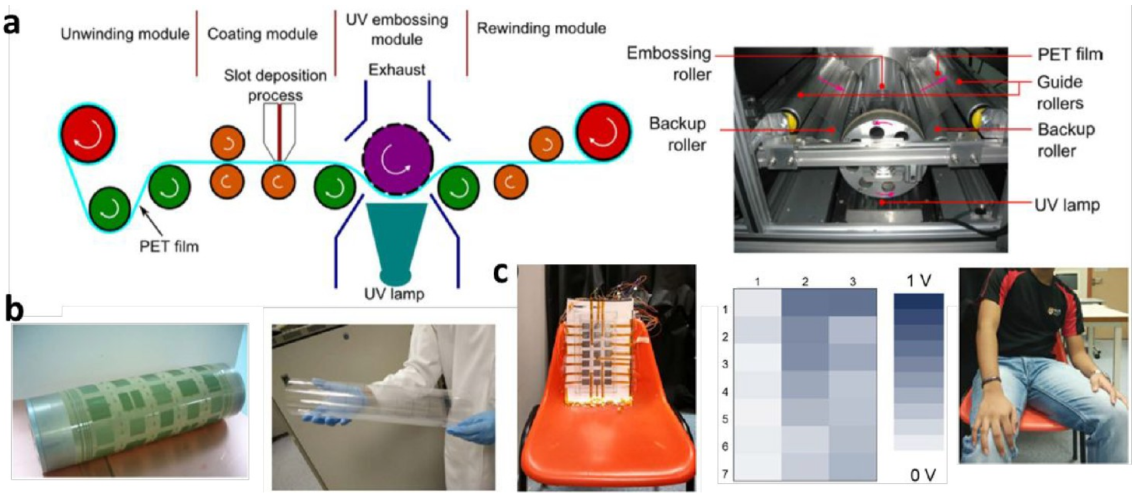

Figure 9. Scalable fabrication techniques to enable large-area applications. (a) Schematic illustration of the fabrication machine for the large-scale TENG using roll-to-roll UV embossing. (b) Photograph of the prepared flexible TENG. (c) Application of the film as a self-powered pressure sensor array. Reprinted with permission under a Creative Commons CC BY License from ref 154. Copyright 2016 The Authors.

large-scale, ultrasoft, and washable smart textile for sleep monitoring.[17] The textile is fabricated with a dimension of 1.5 × 2 m^2, and the key functional elements are 61 independent woven washable fibers with serpentine structures. The functional fiber is made of commercially available materials with a scalable fabrication technique. It has a sheath-core structure with an ultrathin hollow silicone fiber as the outer sheath and a conductive yarn as the inner core. With these sensing elements, the smart textile is capable of simultaneously tracking the dynamic changes in sleep postures and detecting subtle respiration and ballistocardiogram (BCG) changes. This work is expected to bring significant benefits to physiological monitoring during sleeping as well as healthcare monitoring.

Besides the large-scale fabrication of 1D fiber, Yang *et al.* reported a tribo-ferroelectric synergistic e-textile with a dimension of 105 × 35 cm^2, as indicated in Figure 13.[18] All the fabrics in the e-textile are prepared *via* the electrospinning technique. Poly(vinylidenefluoride-trifluoroethylene) (P(VDF-TrFE)) nanofibers are uniformly deposited on Ni−Cu fabric electrode to form the fabric electrode-P(VDF-TrFE) nonwoven fabric, as the outer ferroelectric layer. Next, polyamide 6 (PA6) nanofibers are further deposited on nonwovens to form the fabric electrode-P(VDF-TrFE)-PA6 nonwoven fabric, as the inner ferroelectric layer. These two fabrics are then sewn with the moisture-wicking fabric separately which is also made by sequentially electrospinning PA6 and polyacrylonitrile (PAN) nanofibers onto the hydrophobic breathable cotton fabric. Finally, the two parts are pressed together by cold-compacting post-treatment to improve the interface bonding between the nanofibers. The nanofiber structures of these fabrics enable an outstanding thermal-moisture compatibility of the e-textile. Furthermore, because of the tribo-ferroelectric synergistic effect introduced by ferroelectric polymer nanofibers, the maximum peak power density of the e-textile reaches 5.2 W/m^2 under low-frequency motions, which is 7 times that of the state-of-the-art breathable triboelectric textiles. Then a self-powered gesture monitoring system is developed containing the e-textile, signal transmitting module, and signal receiving module. Gait information during human movement can be captured and transmitted to a smartphone in real-time for human motion monitoring. As shown in Figure 14, Dong *et al.* reported a highly resilient 3D braided TENG as e-textile for energy harvesting and self-powered sensing.[155] The multiaxial winding yarn based on commercial silver-plated nylon yarns is prepared as the electrode through a high-speed rope braiding machine, enabling industrial mass production. Afterward, PDMS is used as the triboelectric layer and coated on the electrode yarn. The 3D braided TENG is formed with the PDMS-coated yarn as the braided yarn and the multiaxial winding yarn as the axial yarn in a self-developed 3D braided machine based on a rectangular braiding technology. Owing to the spatial frame-column structure formed between the outer

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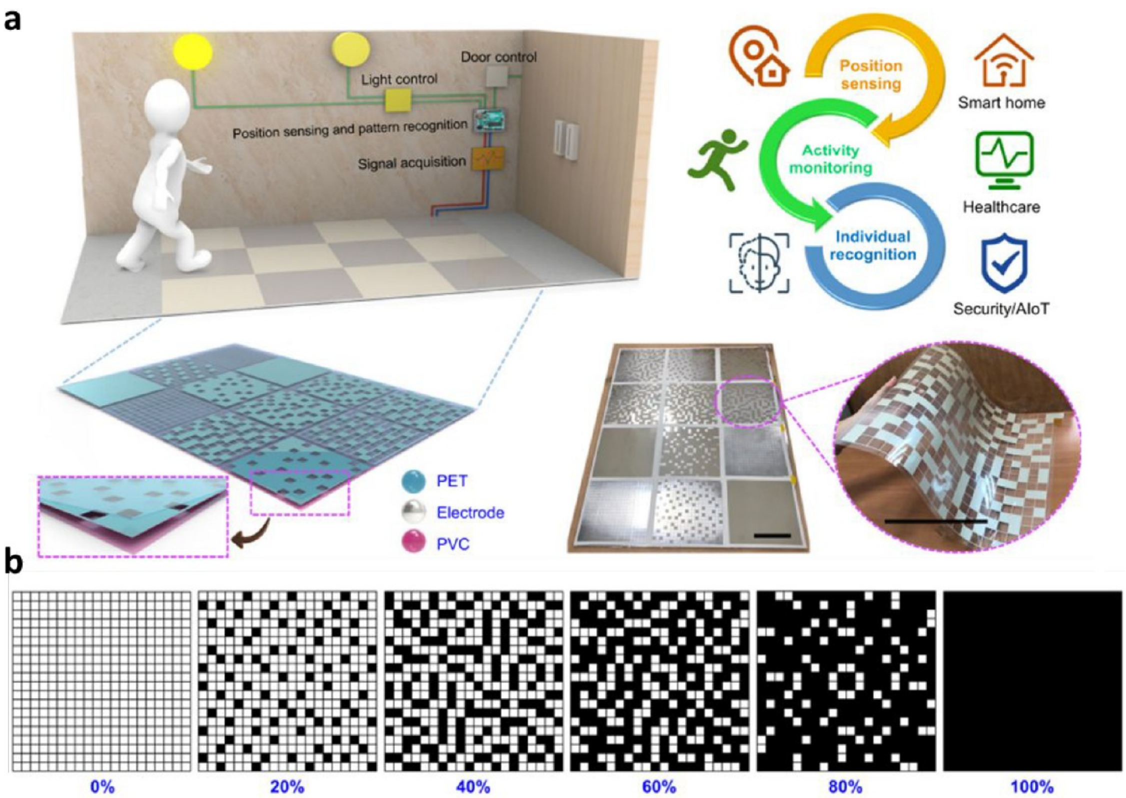

Figure 10. Scalable fabrication techniques to enable large-area applications. (a) Scalable floor mat array enabled by screen printing technology for position sensing, activity monitoring, and individual recognition. (b) Detailed illustration of the six electrode patterns. Reprinted with permission under a Creative Commons CC BY License from ref 22. Copyright 2020 The Authors.

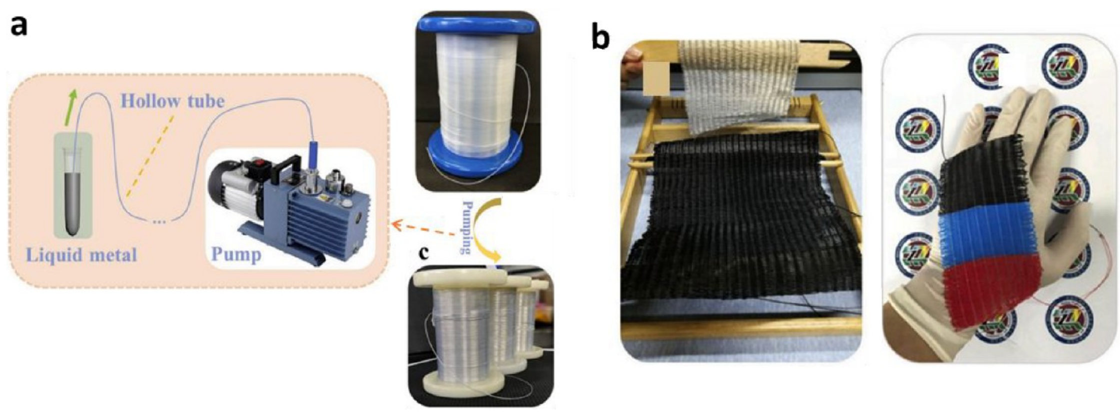

Figure 11. Scalable fabrication techniques for textile-based electronics to enable large-area applications. (a) Fabrication process of robust fiber using pumping method. (b) Knitting process of the textile-based TENG. Reproduced with permission from ref 140. Copyright 2020 Elsevier.

braided yarn and the inner axial yarn, the 3D braided TENG not only can function as an energy harvester but also can have high compression resilience and improved pressure sensitivity. An intelligent shoe and an identity recognition carpet are demonstrated for smart home applications. Overall, with the developed scalable fabrication technologies, there is potential for the flexible devices to advance toward mass production and commercial applications.

4. AMBIENT DEVICES WITH GENERIC FUNCTIONALITIES

With the developed functional materials and fabrication techniques, diversified devices including ambient devices and wearable devices according to their respective usage scenarios can then be manufactured for smart home applications. Ambient devices deployed in the home areas are able to provide generic functionalities that are not limited to particular individuals, which is important to achieve convenient, continuous, and ubiquitous monitoring and responsiveness in the home setting.[19,22,156−158] These ambient devices such as various forms of sensors can be implemented at different locations, *e.g.*, door, floor, table, chair, bed, toilet, window, and wall, to enable multifunctionalities including access control, security, indoor positioning, fall detection and alarm, human−machine interaction, automation, amenity regulation, health care, disabled assistance, *etc.*

In buildings and homes, doors are the first option of access regulation, and thus, their vulnerability to intrusion would be a

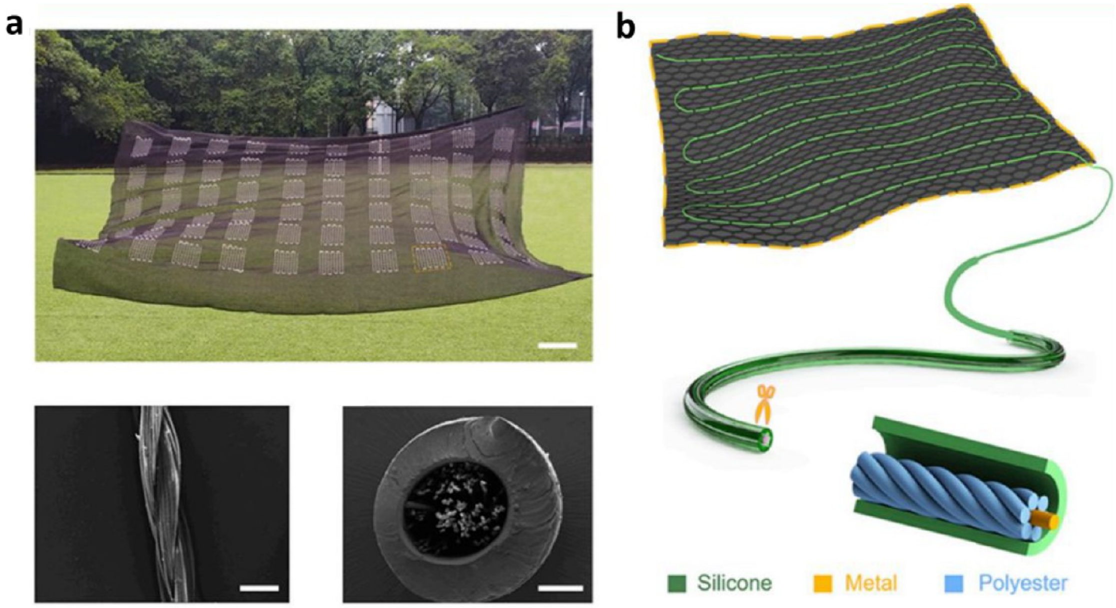

Figure 12. Scalable fabrication techniques for textile-based electronics to enable large-area applications. (a) Large-scale, ultrasoft, and washable TENG textile for sleep monitoring. (b) Detailed illustration of the single fiber. Reproduced with permission from ref 17. Copyright 2020 Elsevier.

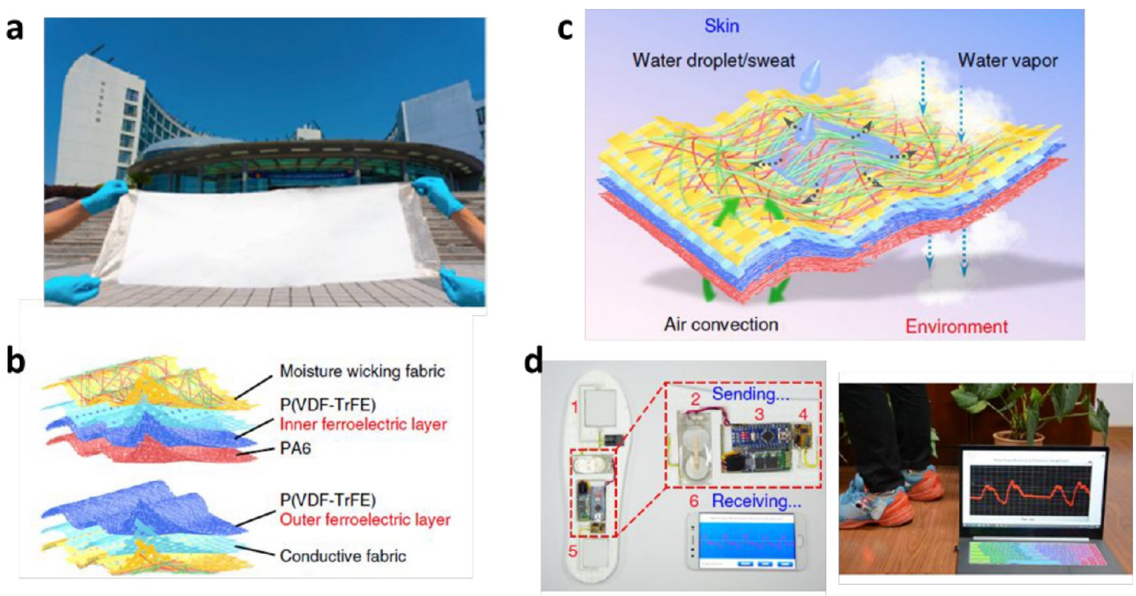

Figure 13. Scalable fabrication techniques for textile-based electronics to enable large-area applications. (a) Electrospinning enabled large-scale, all-fiber based tribo-ferroelectric e-textile. (b) Structural illustration of the tribo-ferroelectric e-textile. (c) Illustration of the e-textile with high thermal-moisture stability and comfortability. (d) Self-powered gesture monitoring system that captures gait during human movement and transmits it to a smartphone or computer in real time. Reprinted with permission under a Creative Commons CC BY License from ref 18. Copyright 2019 The Authors.

great security concern. In order to improve the safety level and tracking capability of doors, advanced sensors with secure data encoding can be employed.[39,159,160] An example of such implementations is illustrated in Figure 15, where Chen *et al.* reported a triboelectric sensor-based barcode recognition system for assisting personal identification and access control.[159] The whole system mainly consists of an information card with a user and a reader deployed beside a door. To access the door, the user can just simply swipe the card on the reader. If the person is an authorized user, then the door will be opened by the control circuitry automatically. The user's personal information is encoded with barcode electrodes on one side of the card, while reference electrodes are fabricated on the other side to eliminate the influence of swiping speed. Based on the triboelectric mechanism during swiping, each electrode will induce an electrical pulse on the reader from the same side. Since the reference electrode is designed with a regular pattern, thus by referring the pulses from the information reader output to the reference reader output, the encoded information as well as the user's identity can be recognized. The detailed comparison scheme is as follows: (1) determining the coding positions through the positive peaks and negative peaks of reference output; (2) for the reference code, a positive peak is "1" and a negative peak is "0"; (3) if

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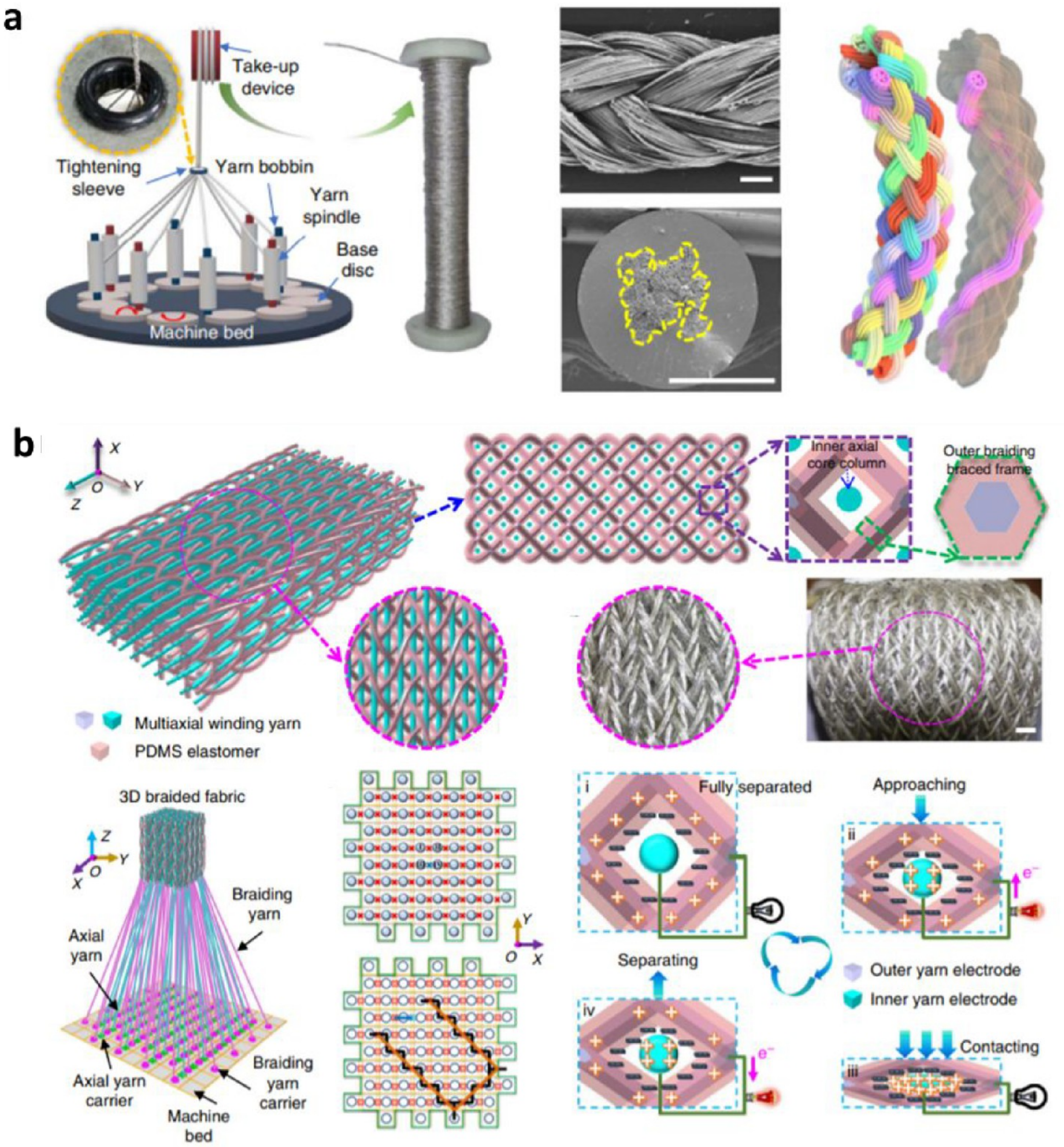

Figure 14. Scalable fabrication techniques for textile-based electronics to enable large-area applications. (a) Fabrication machine and process of the energy yarn. (b) Fabrication of the large-scale and highly resilient 3D braided e-textile for energy harvesting and self-powered sensing. Reprinted with permission under a Creative Commons CC BY License from ref 155. Copyright 2020 The Authors.

there is the same polarity peak at a certain determined position, then the information code is the same as the reference code (such as the first three digits in the figure); (4) if there is an opposite polarity peak, then the information code is also opposite to the reference code (such as the fifth digits in the figure); (5) for all the other positions without any peaks in the information output, the coding digit is the same as the formerly determined digit (such as the fourth digit is the same as the third digit, and the sixth digit is the same as the fifth digit). With such a recognition system, not only can the access control and door automation be achieved with high security, but also information tracking such as the number of users and usage time can be obtained for administrative purposes in the COVID-19 pandemic.

The floor, comprising a large area in homes, is one of our most frequently engaging interfaces in daily activities, which carries abundant information of our behavior status and abnormal events such as object dropping and falling. Besides, our daily activities like walking and exercising also contain ample mechanical energy that is normally wasted. To extract information or harvest energy from human activities, self-powered devices with dual functionality as both a sensor and energy harvester can be embedded on the floor.[161−163] One recently developed example is shown in Figure 16, where Gu *et al.* proposed a cellulosic material-based TENG floor tile for both activity sensing and energy harvesting.[164] The TENG floor tile uses natural wood as the substrate to be compatible with current floors and integrates multiple layers in the vertical direction for higher performance. Moreover, due to the enormous difference in the electron affinity of the two adopted triboelectric materials, *i.e.*, weighing paper and nitrocellulose paper, the fabricated multilayered TENG floor tile shows a great output performance (360 V, 250 μA, and 5 mW in terms of maximum output voltage, current, and power, respectively). The harvested energy can be stored in supercapacitors or batteries for powering other IoT sensors and systems. Next, to

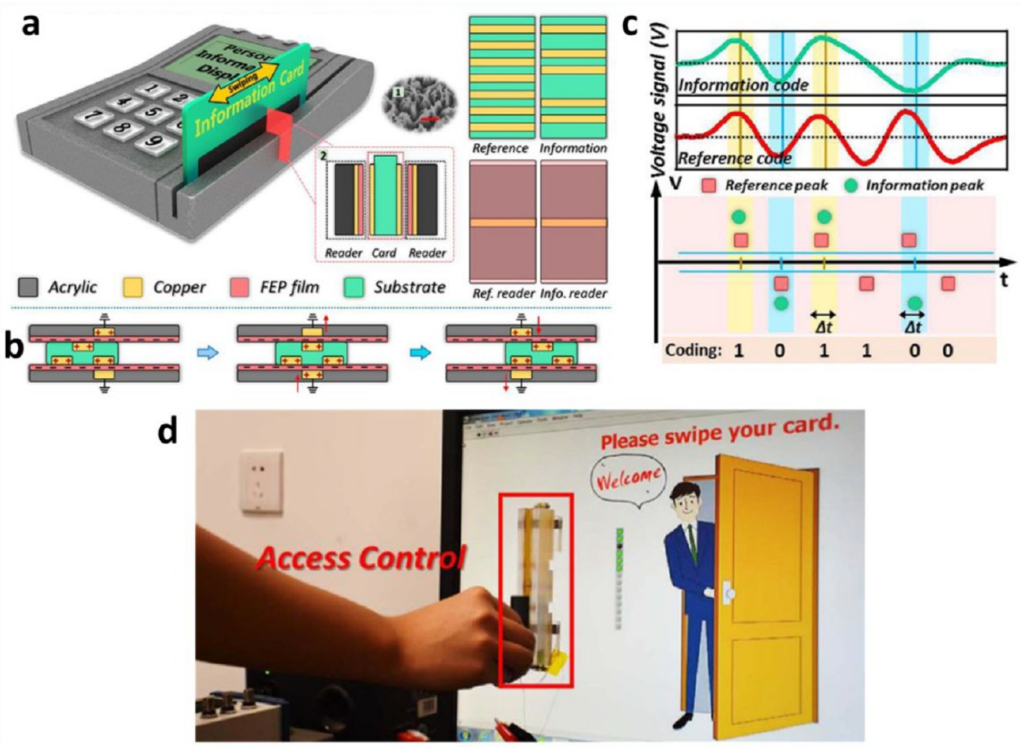

Figure 15. Ambient triboelectric based barcode recognition system deployed besides the door for personal identification and access regulation. (a) System schematic and device structure. (b) Operation principle. (c) Example of the generated signals and coded information. (d) Access control demonstration. Reproduced with permission from ref 159. Copyright 2018 Elsevier.

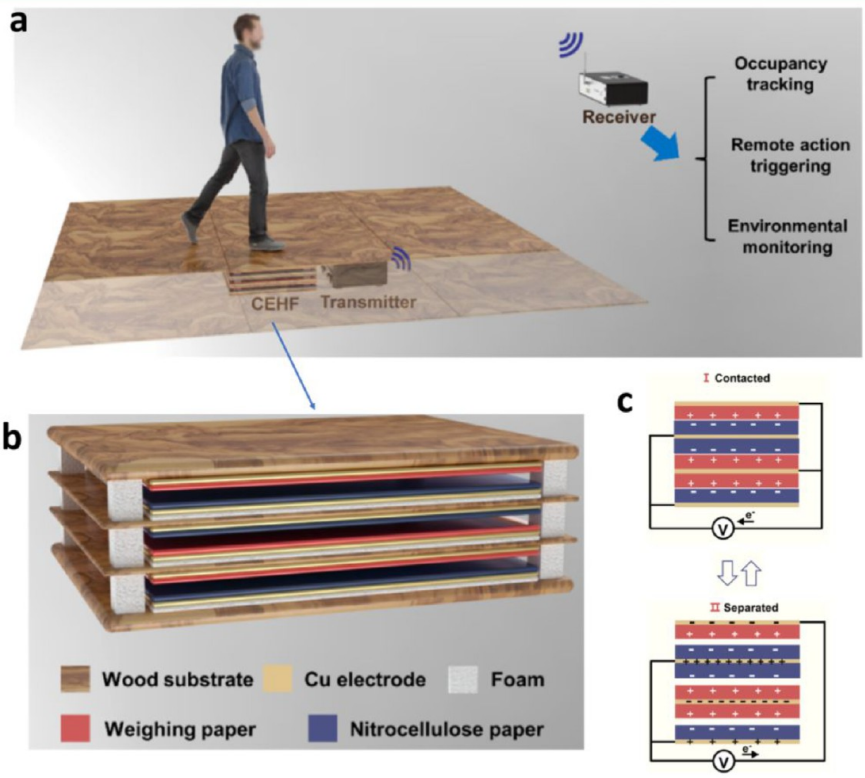

Figure 16. Cellulosic material-based TENG embedded on the floor for indoor monitoring and energy harvesting. (a) Application scenario overview. (b) Detailed device structure. (c) Operation principle. Reproduced from ref 164. Copyright 2021 American Chemical Society.

enable activity monitoring, an array of the TENG floor tiles could be implemented to cover the interested area. By analyzing the sensory outputs in the time domain, the user's stepping position, walking trajectory, exercise type, and room

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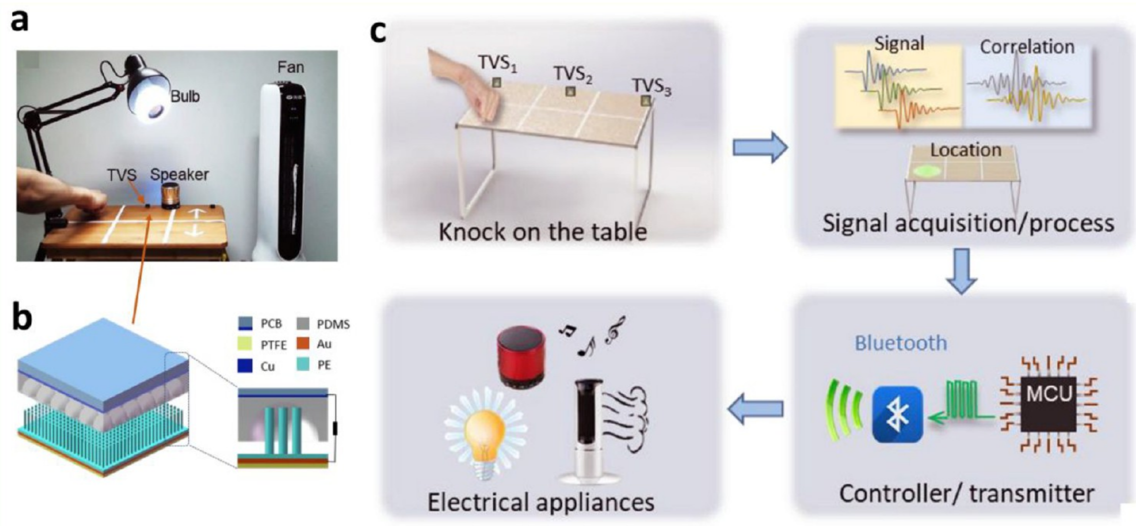

Figure 17. Triboelectric vibration sensors integrated on a table for detecting and positioning an interactive vibration source. (a) Digital photograph of the interaction. (b) Detailed device structure. (c) Flow diagrams of the signal generation, process, and control communication. Reproduced with permission from ref 165. Copyright 2019 Elsevier.

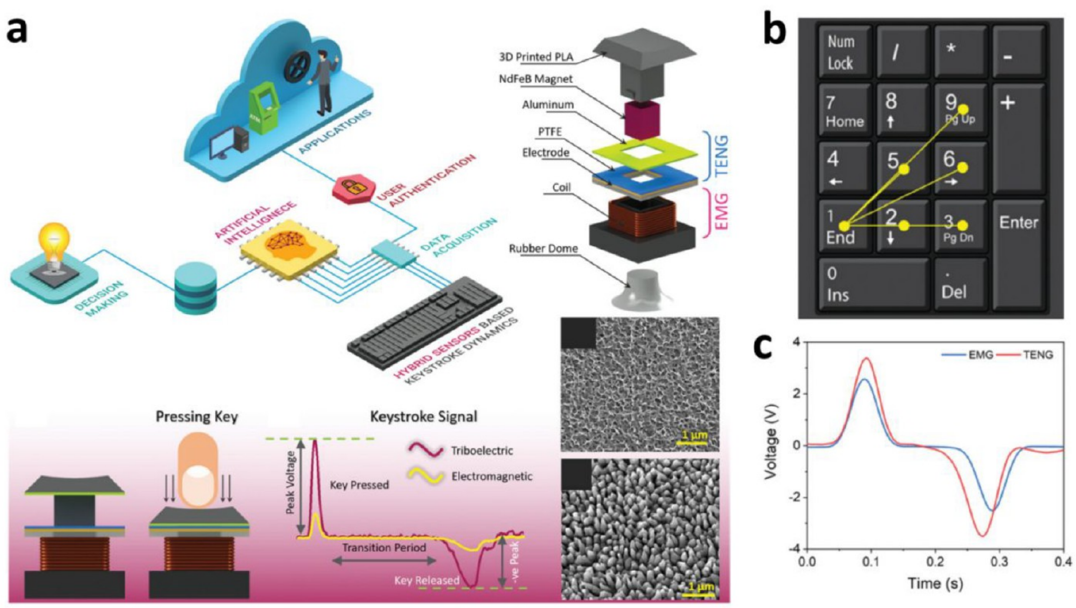

Figure 18. Hybrid sensor integrated on a keyboard for keystroke dynamics-based and biometric-protected authentication. (a) Device structure and application scenario. (b) Digital photograph of the integrated keyboard. (c) Signal output when pressing a key. Reproduced with permission under a Creative Commons CC-BY license from ref 166. Copyright 2021 The Authors.

occupancy could be obtained. Furthermore, if ML or DL algorithms are employed to extract the gait-induced features from the generated waveforms, user identity recognition could then be achieved for more diverse applications in smart homes.[22]

Similarly, tables, chairs, and other furniture can also be embedded with advanced sensors for monitoring and interactive applications. As indicated in Figure 17, He *et al.* designed a triboelectric-based surface vibration sensor with a broad sensing range and integrated three units of them on a table for detecting the position of finger tapping.[165] Instead of implementing an array of sensor pixels on the entire table surface, the authors use only three sensors for the position detection of a vibration source, based on the arrival time difference between the three sensors. These parameters are correlative to the distance between the vibration source and each sensor, from which the tapping position on the table can then be derived. This detecting mechanism leads to a facile configuration and a simplified data process for the table sensing system. To enable accurate position detection, vibration sensors with high sensitivity and fast response time are required. Thus, a structure mimicking the fish's ampulla is designed for the triboelectric vibration sensor, enabling the detection of minute vibrations. Such a structure realizes an excellent force sensitivity of 0.97 V/N (<1 N) and a wide frequency range of 1−3 kHz. With three units integrated on a table, arrival time difference and signal correlation analysis can be performed to locate the interactive vibration source on the table surface. In a demonstration, an ordinary table is divided into six sectors and utilized as an intelligent and multifunc-

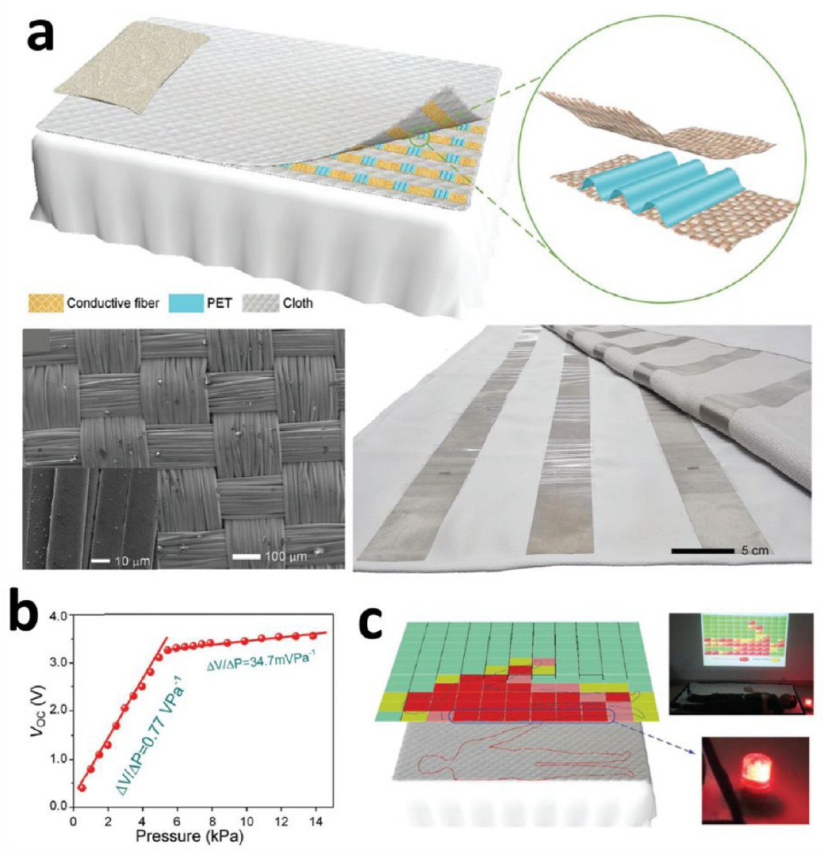

Figure 19. Large-scale, washable, and textile-based triboelectric pressure sensor array on the bed for sleep behavior monitoring. (a) Device schematic, SEM image of the conductive textile, and digital photograph. (b) Pressure sensing response. (c) Example of user posture display and alarm. Reproduced with permission from ref 167. Copyright 2018 John Wiley and Sons.

tional interactive system for convenient electrical appliance control, such as a bulb, fan, speaker, *etc.* Moreover, other surfaces such as cabinet doors and walls could also be converted into intelligent interactive interfaces with the developed vibration sensors.

The keyboard is an important component to link up the real world and the digital world for work, study, finance, and entertainment, which we frequently use in offices and homes. Today, cyberattacks are a great concern for digital security. To evolve from the current password-based authentication that is vulnerable to common attacks (such as dictionary attacks), Maharjan *et al.* designed a keystroke dynamics-based and biometric-protected authentication system through integrating keyboard sensors with AI (Figure 18).[166] The developed keyboard sensor hybridizes EMG and TENG to effectively convert the keystroke motion into electrical signals that contain unique behavioral information about a user's typing habits. The generated signals are then fed into a neural network algorithm for the purpose of biometric-protected user authentication, achieving a high classification accuracy of 99%. Together with the traditional password input, the integrated authentication system provides a more secure and promising approach against password vulnerability, where not only the password needs to be correct, but also the user's behavioral keying needs to match with the authorized user.

The time we spend in bed every day is around one-third, which is even longer for some patients. Thus, it is of great significance to monitor our health status in bed, especially for those with sleeping disorders.[17,167] To enable convenient monitoring without influencing the sleeping quality, flexible or textile sensors over their rigid counterparts are more preferable. In this regard, Lin *et al.* developed a large-scale, washable, and textile-based triboelectric pressure sensor array for behavior monitoring during sleep (Figure 19).[167] Conductive textiles are adopted to fabricate the column electrodes and row electrodes of the array in two separate cloths that can cover the entire bed area. Then waving PET films are assembled at the electrode intersections as the negative triboelectric material. Under pressure, the PET film will contact the conductive textiles, generating electrical outputs on the respective column and row electrodes and enabling position detection at that pixel. This material and structural design provides the desirable characteristics in sleep monitoring, such as high sensitivity, good durability, rapid response, great convenience, and water resistance. Next, a data acquisition module, a signal processing module, and a wireless transmission module are integrated with the sensor array to achieve the real-time functionality of sleep behavior monitoring. For instance, the position and posture of a user in bed can be viewed with a display program on a remote computer. In addition, an alarm can be triggered by the monitoring system when a user such as an elderly nonhospitalized patient is about to fall from the bed, to wake up the user or alert other family members for immediate action in a remote medication scenario.

In certain circumstances in homes, noncontact and remote interactions will be helpful, such as with dirty/wet hands or busy with both hands. Sound could be a good medium to

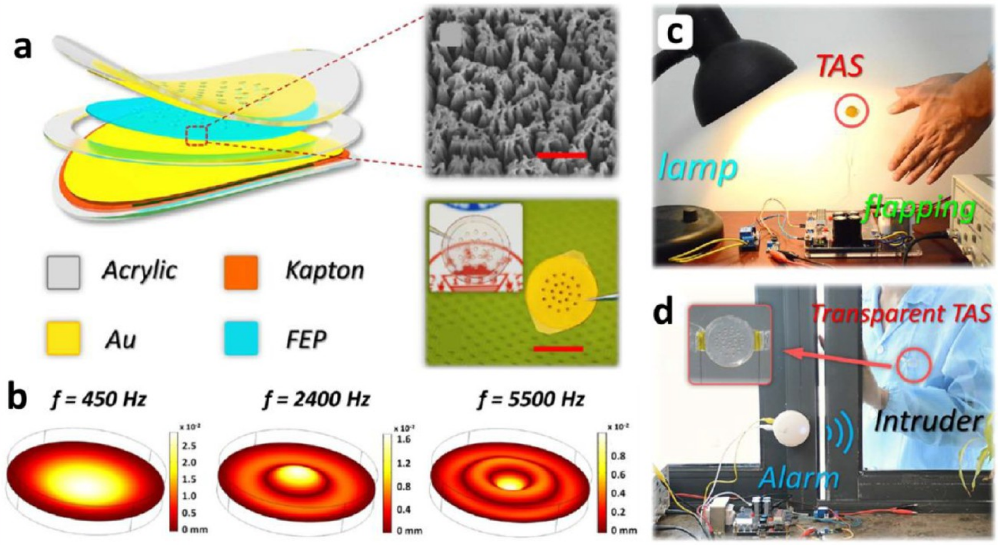

Figure 20. Triboelectric sensor enabled electronic auditory system toward remote and intelligent sensing applications. (a) Device structure. (b) Three resonant modes. (c) Desk lamp controlled by hand movement. (d) Sound-based antitheft system. Reproduced with permission from ref 171. Copyright 2018 The American Association for the Advancement of Science.

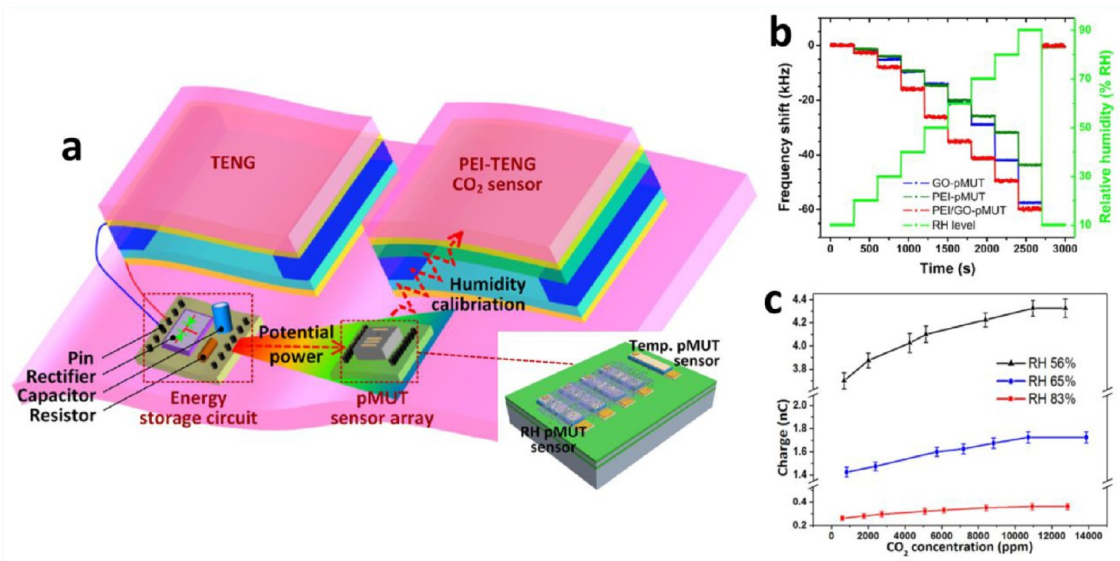

Figure 21. Smart-home multifunctional platform for simultaneous monitoring of CO_2 concentration, temperature, and relative humidity. (a) Platform schematic and device structure. (b) Humidity sensing response by the pMUT array. (c) CO_2 sensing by the PEI-TENG. Reproduced with permission from ref 19. Copyright 2019 Elsevier.

enable noncontact and remote monitoring as well as interaction/control in smart homes due to its great convenience and high distinguishability between individuals.[168−170] As shown in Figure 20, Guo *et al.* proposed a self-powered triboelectric sensor for the construction of an electronic auditory system toward intelligent sensing and remote control applications.[171] The triboelectric sensor is mainly composed of a suspended Au/Kapton membrane and a fixed fluorinated ethylene propylene (FEP) film, supported by acrylic frames with holes. With an incoming sound wave, the suspended membrane vibrates responsively and periodically contacts the fixed FEP for output generation. Due to the specific structure design, the triboelectric sensor exhibits an ultrahigh sensitivity of 110 mV/dB and a broad operation bandwidth of 100−5000 Hz with three distinctive vibration modes. These excellent characteristics enable the recording of high-quality music and the recognition of different voices. Afterward, an electronic auditory system is constructed using the triboelectric acoustic sensor and back-end circuitry for the remote control of a desk lamp by hand movement. Moreover, by using transparent materials (PET, ITO, graphene, *etc.*) to fabricate the triboelectric acoustic sensor, a sound-based antitheft system is built for smart home security, which can detect the sound and trigger an alarm when an intruder is trying to unlock the window.

Other than the above-mentioned physical sensors for the event-based monitoring, chemical sensors like gas sensors are indispensable components in smart homes as well, to enable automatic air-conditioning, higher levels of living comfort, and home safety.[19,172−174] In this regard, Sun *et al.* presented a

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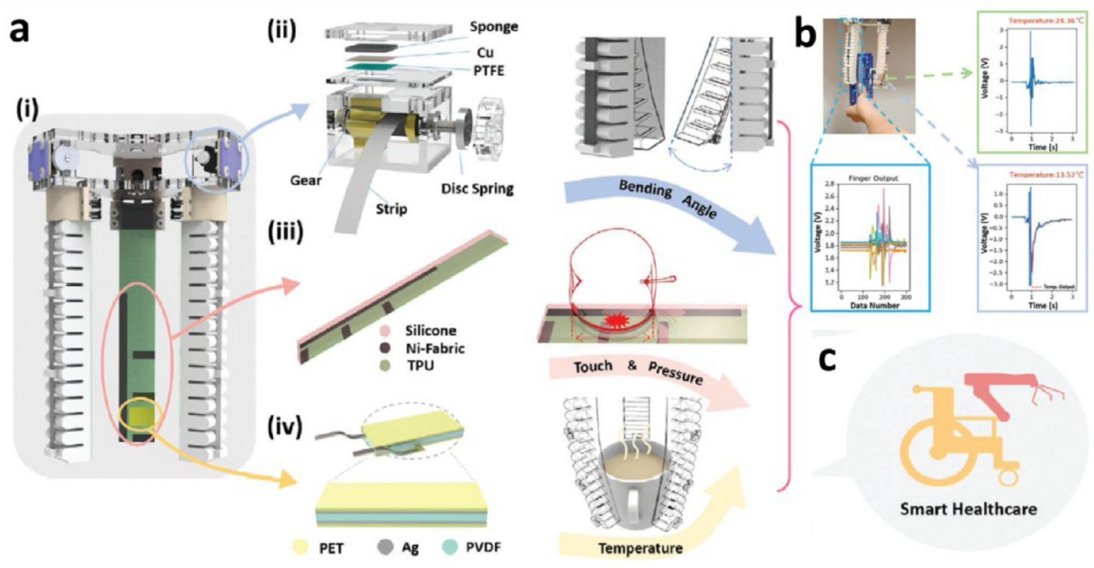

Figure 22. Soft robotic hand with multimodal sensors for virtual shopping and home assistance. (a) Multiple sensors on the robotic hand. (b) Generated signals during a grasp motion. (c) Potential application for smart healthcare. Reproduced with permission under a Creative Commons CC-BY license from ref 21. Copyright 2021 The Authors.

multifunctional monitoring platform for simultaneous detection of CO_2 concentration, temperature, and relative humidity in home environments (Figure 21).[19] The CO_2 sensing capability is enabled by a contact-separation triboelectric sensor with a polyethyleneimine (PEI) coating as the selective material. Different amounts of CO_2 absorption and the following chemical reactions modify the charge quantity on the triboelectric surface, thus generating corresponding outputs when actuated. On the other hand, the temperature and relative humidity sensing abilities are achieved using an array of piezoelectric micromachined ultrasonic transducers (pMUTs). The frequency drift over the temperature of a pMUT without any coating is employed for temperature sensing. Then PEI/graphene oxide (GO) is coated on the rest pMUTs for humidity sensing. If the ambient humidity increases, more water molecules will be absorbed by the PET/GO film, leading to a lower resonant frequency of the pMUTs due to the mass loading effect. Besides these sensing components, a triboelectric energy harvester is also integrated for scavenging the biokinetic energy and serving as a potential power source for other sensors. Overall, the developed multifunctional platform enables the continuous monitoring of various amenity parameters in smart homes, which can be adopted as a reference for home autocontrol and safe-guarding. Furthermore, the detection capability of the platform can be extended by adding more sensors with selective layer coating, for the critical monitoring of certain toxic gases such as formaldehyde.

Except for versatile monitoring functionalities, home assistance is another important aspect for modern smart homes, in particular for the elderly and the disabled. Recently, soft robotics has gone through rapid development in various assistive applications, emerging as a promising candidate for safe and delicate assistance.[175−178] As illustrated in Figure 22, Sun *et al.* designed a soft robotic hand with multimodal sensors for the potential applications of industrial automation, virtual shopping, and home assistance.[21] The robotic hand integrates triboelectric tactile sensors, triboelectric bending angle sensors, and PVDF-based pyroelectric temperature sensors, in order to obtain multimodality sensory information of a grasped object such as shape, size, material, and temperature. Then by using DL to extract features from the multichannel triboelectric outputs, the robotic hand can achieve the recognition of grasped objects, with an accuracy of as high as 97.14% for a data set with 28 different objects such as various fruits, boxes, cans, and bottles. Meanwhile, the object temperature sensing or mapping can also be obtained by using one or more pyroelectric sensors. Thus, the soft robotic hand is demonstrated as an assistive tool in online virtual shops to provide real-time feedback to users in the augmented virtual space after they select the goods. In the smart home scenarios, it can serve as an assistive tool for the elderly and the disabled, *e.g.*, grasp assistance and garbage classification, *etc.*

5. WEARABLE DEVICES

In addition to the ambient devices, the rapid development of numerous wearable electronics creates a large variety of wearable applications,[29,179,180] which are of great importance to extend the smart-home scenarios and realize personal monitoring, such as continuous health monitoring, elderly/children care, fall detection, disabled assistance, body motion monitoring, and human−machine interactions.[181−189] Hence, in this section, some recently developed wearable technologies for smart healthcare and rehabilitation will be reviewed.

When considering the diseases that endanger human health, cardiovascular disease is currently one of the most common causes of death worldwide. To enable continuous cardiovascular monitoring, wearable sensing technologies have been developed recently to collect arterial pulse waves that contain comprehensive cardiovascular information for monitoring and diagnosing arterial stiffness related to hypertension.[190,191] Among them, wearable sensors based on the triboelectric mechanism have drawn great attention due to the merits of self-powered outputs, low cost, and high sensitivity. However, their relatively weak pulse wave signal and environmental influences, *e.g.*, humidity, still hinder their applications for actual usage. To address these issues, Fang *et al.* proposed a low-cost textile TENG sensor for continuous pulse waveform monitoring as illustrated in Figure 23.[192] The outer textile layer

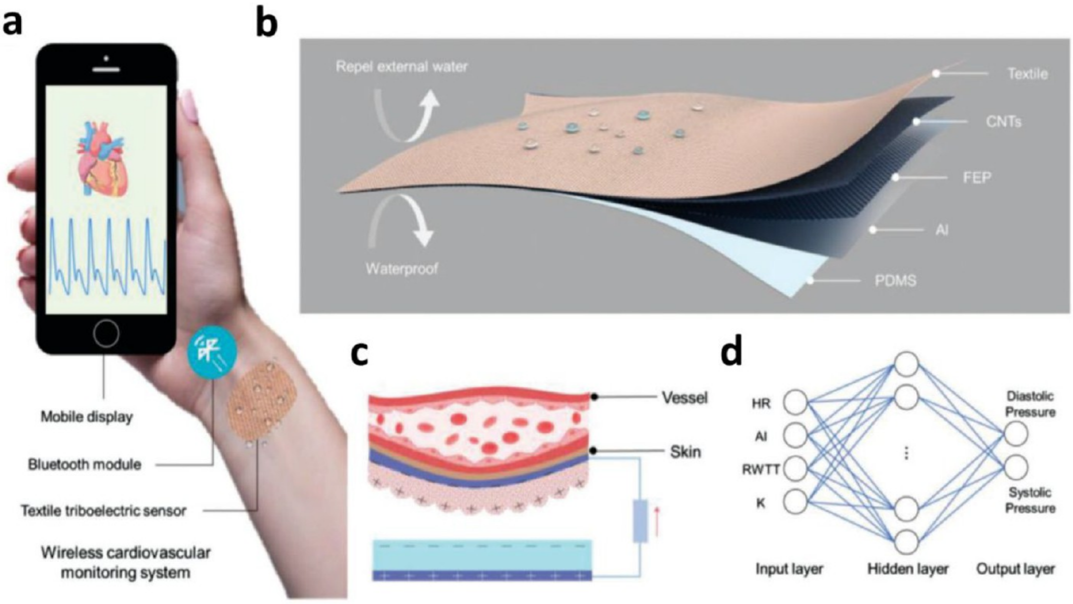

Figure 23. Low-cost textile TENG sensor for continuous pulse waveform monitoring. (a) Illustration of the cardiovascular monitoring system. (b) Structure of the TENG sensor. (c) Working mechanism of the TENG sensor. (d) Neural network for blood pressure prediction. Reproduced with permission from ref 192. Copyright 2021 John Wiley and Sons.

acts as both a protective layer against airflow noise due to body motions and a waterproof layer to repel external moisture. The inner PDMS layer has been proven as effective waterproof material in bioelectronics. The structured CNTs and FEP triboelectric layers enable the sensor with a high sensitivity of 0.21 μA/kPa and a good signal-to-noise ratio of 23.3 dB. The fast response time of 40 ms also ensures its real-time detection capability. After mounting the sensor on the waist skin and applying ML analytics, precise systolic and diastolic pressure information could be extracted from the skin deformation-caused signal waveform, for which the accuracy is quite close to the result achieved by a commercial blood pressure cuff. With a wireless module for data transmission, a customized smartphone application is also successfully built to conveniently share the health data under the smart home internet framework toward personalized healthcare in the IoT era.

Human respiration is also an important index to evaluate the health status, and the corresponding monitoring could be used for forecasting many health problems, *e.g.*, obstructive sleep apnea-hypopnea syndrome (OSAHS), lung disease, asthma, *etc.*[193] Due to the advantages of high flexibility and comfort, the emerging sensing techniques using the TENG-based e-skins are quite suitable to be used for fine respiration monitoring without causing obvious skin discomfort, inflammation, or itching.[25,194−196] As shown in Figure 24, Peng *et al.* developed a nanofiber-based TENG e-skin with strong air permeability, high flexibility, high sensitivity (0.217 kPa^{-1}), and good stability.[197] Because of the many available choices of triboelectric materials, all components in the sensor can be nanofiber-based through an implementable electrospinning strategy, endowing the monitoring device with good wearing comfort to be attached to human skin for daily usage. Moreover, the 3D micro-to-nano hierarchical structures also greatly enlarge the surface area for contact electrification and thus enhance the output signal. By attaching the sensor patch to the user's abdomen, the subtle respiratory information including respiratory rate, interval, and intensity could be collected in real-time and simultaneously. In addition, a self-powered diagnostic system is also established to evaluate the severity of sleep apnea, hypopnea, and OSAHS, so as to provide auxiliary evaluation for medical diagnosis.

Work-related upper extremity musculoskeletal disorders (MSDs) are common joint-related diseases in our lives, especially for those who sit and work in front of the computer for a long time.[198] To prevent MSDs, developing a wearable sensing system capable of continuously monitoring joint motion during daily activities and giving warnings when appropriate is a good strategy. Due to the rapid response to mechanical deformation, flexible piezoelectric sensors show great potential to be integrated into wearable systems for physiological information monitoring. However, most of them are not stretchable and are not applicable for joint motions with large strain and multiple degrees of freedom. Based on these considerations, a highly anisotropic piezoelectric ceramic-electrical network composite sensor with a kirigami structure was proposed by Hong *et al.*, which can monitor and distinguish various pieces of information about joint motion, including bending direction/radius and motion modes because of the great ability of kirigami to transfer structures from stiff to stretchable forms.[199] With the special template-assisted processing method, the designed honeycomb network structural piezoceramic kirigami shows good stretchability (~100% strain) and high sensitivity (15.4 mV/kPa) as well as the desired high-dimensional anisotropy for stress measurement from all directions in a plane. The developed bending sensor has been demonstrated to have a large measurement range and high accuracy of neck monitoring, which can alert people to the problem of sitting for long periods of time and exercising regularly. The emergence of this kind of new sensor demonstrates the possibility to effectively prevent upper limb MSDs and other joint-related diseases. Another disease that could be monitored *via* the joint-attachable wearable sensor is Parkinson's disease (PD), with symptoms of tremors in the legs and hands.[200,201] As illustrated in Figure 25, Kim *et al.*

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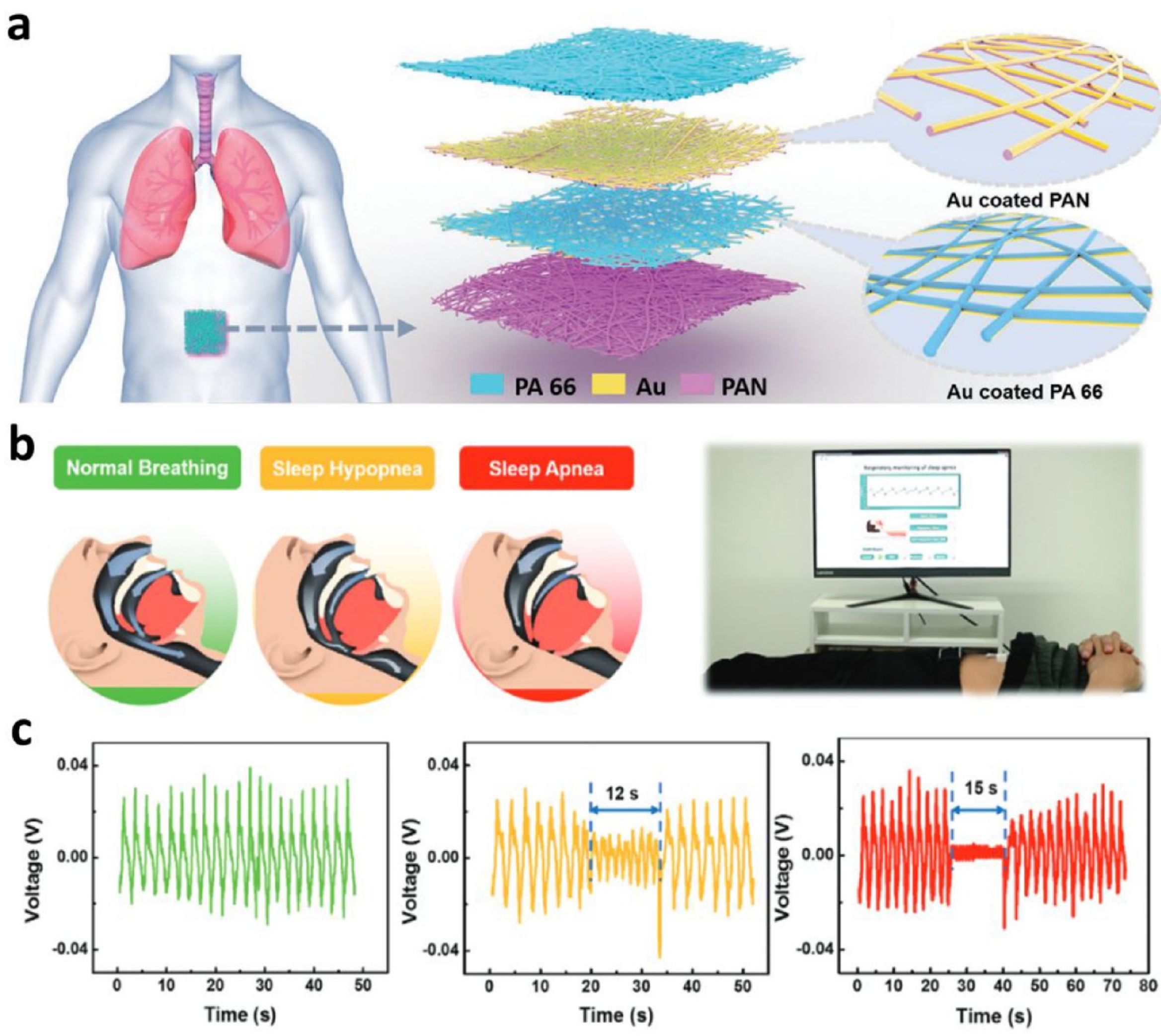

Figure 24. Nanofiber-based TENG e-skin for fine respiration monitoring. (a) Structural design of the e-skin. (b) Obstructive sleep apnea-hypopnea syndrome diagnosis system. (c) Output signals for different sleep respiratory states. Reproduced with permission from ref 197. Copyright 2021 John Wiley and Sons.

proposed a self-powered tremor sensor composed of an M-shaped Kapton film and a catechol-chitosan-diatom hydrogel enabled TENG.[202] The developed self-healable biohydrogel electrode shows good compatibility with flexible/stretchable devices and has good adhesion on both hydrophilic and hydrophobic surfaces, making it attachable to skin surfaces in a variety of conditions. The M-shaped structure significantly enhances the sensor sensitivity and shortens the total response time, which is quite suitable to be used for patients' low-frequency vibrational motion detection. By using the ML algorithm of linear support vector machine for further data analysis, three types of tremors including normal, minor, and severe could be identified with 100% probability, revealing the effectiveness of such a wearable monitoring system for PD prevention.

Though the above-mentioned self-powered joint sensors show potential for flexible wearable systems for real-time human motion detection or health monitoring in smart homes, most of them collect the output amplitude-based sensory information which is unstable and cannot always provide accurate measurements due to many influencing factors.[203,204] To address this issue, Zhu *et al.* developed a smart exoskeleton that can continuously detect the upper-limb motion based on a grating-sliding structural TENG sensor, as shown in Figure 26.[205] Different from those sensors that judge the joint motion *via* the output amplitude, this kind of sliding-mode TENG rotational sensor can precisely and continuously quantify the rotating degree and speed *via* the generated peak numbers, which is more intuitive and less susceptible to environmental factors like humidity. In this rotational sensor, the PTFE films are patterned with equal intervals. When the Cu spring slides across the PTFE grating pattern surface, triboelectric peaks can be generated due to the variation of induced potential during rotation, where the rotating degree could be achieved *via* the peak numbers and the rotating speed could be extracted from the time interval between two peaks. With well-designed grating patterns, the minimum resolution of the exoskeleton can reach 4°. This kind of device can be further utilized as advanced human-machine interfaces (HMIs) for virtual game control, virtual sports training, and rehabilitation applications to enhance the entertainment experience in smart homes. Based on the similar grating-sling structure, a badge-reel-like stretch sensor was reported by Li *et al.* to detect the spinal bending motion, as shown in Figure 27.[206] By integrating the

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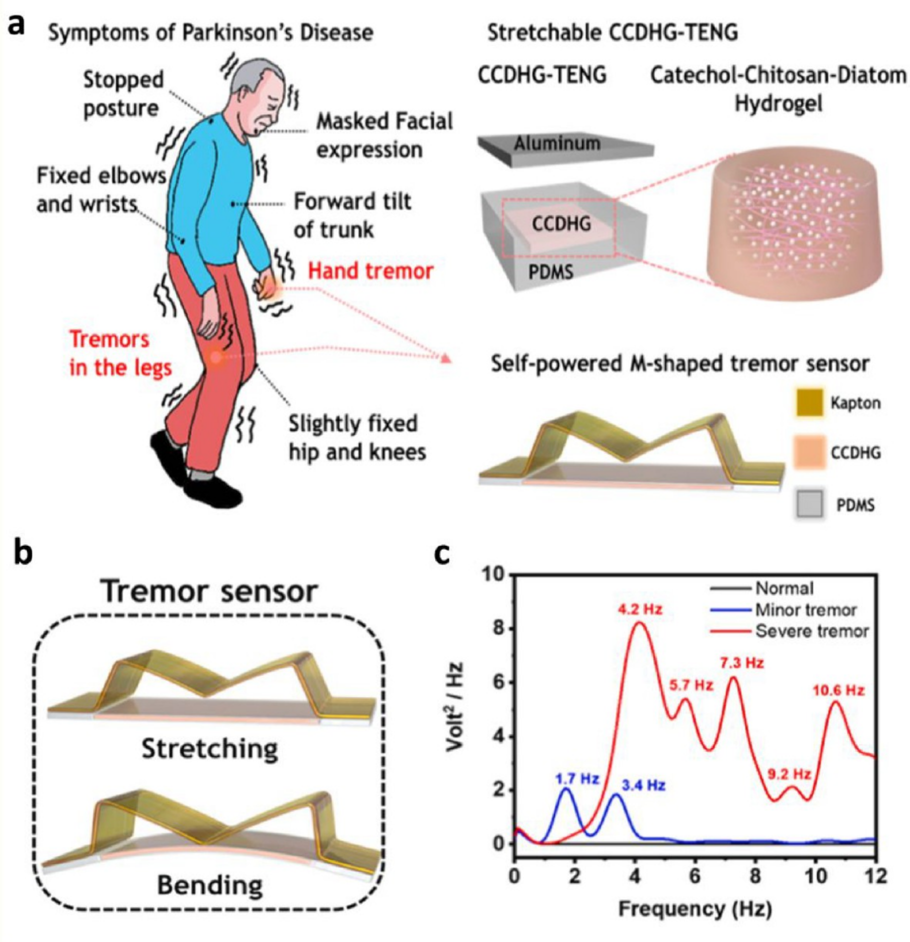

Figure 25. Self-powered M-shaped TENG tremor sensor for Parkinson's disease prevention. (a) Typical symptoms of Parkinson's disease and structure of the tremor sensor. (b) Illustration of the sensor under stretching and bending. (c) Power spectral density of voltage signal from tremor sensor for various motions. Reproduced with permission from ref 202. Copyright 2021 Elsevier.

sensor onto a rehabilitation brace, patients' spinal shape change could be monitored with a minimum resolution of 0.6 mm and a high sensitivity of 8 V/mm. This wearable monitoring system shows good robustness and low hysteresis, which is suitable for long-term continuous monitoring in varying indoor environments.

In addition to the physical-related sensory information, relevant physiological parameters also play an important role in monitoring people's daily health conditions and can be utilized as a valuable reference for medical diagnosis in smart homes.[207,208] Based on this consideration, Li *et al.* developed a self-sustainable wearable sweat sensor as depicted in Figure 28.[64] Different from the above-mentioned works that use mechanical sensors based on piezoelectric/triboelectric materials for physiological information monitoring, the flexible PENG unit in this work is to collect the biomechanical energy of human joint movements during daily activities, which can be further utilized as the power source of the sweat sensor array, *i.e.*, ion-selective electrodes, to achieve a battery-free system. The integrated ion-selective electrodes in the sweat sensor patch show good performance in terms of Na+, K+, and pH sensing, and such information could be directly transmitted *via* a wireless module for further visualization and diagnostic analysis.

6. SELF-SUSTAINED IoT SYSTEMS

To realize higher levels of living comfort and home convenience, diverse ambient and wearable devices are implemented for various monitoring, assistive, and security functionalities as discussed in the previous sections. Furthermore, they can be interconnected under the IoT framework to enable mutual communications with each other as well as the cloud server, for a higher system-level governing of monitoring and responses. Due to the huge number and the widespread distribution of these devices in various locations, the overall power consumption for continuous functionality is significant, and remarkable effort is needed for the replacement of the batteries. Thus, it is of great importance to enable self-sustained devices and IoT systems in smart homes, which have received extensive research interest in the past few years.[209−214]

To achieve self-sustainability, one broadly adopted approach is integrating energy harvesters, power management circuits, and energy storage units into the system.[160,215−217] As indicated in Figure 29, Qiu *et al.* developed a self-powered human−machine interactive system for smart-home appliance and access control.[218] The interactive system consists of a 3-bit encoded triboelectric sensor for sliding motion sensing and interaction, a photovoltaic cell for power supply, and a customized electronic circuit for signal processing and wireless

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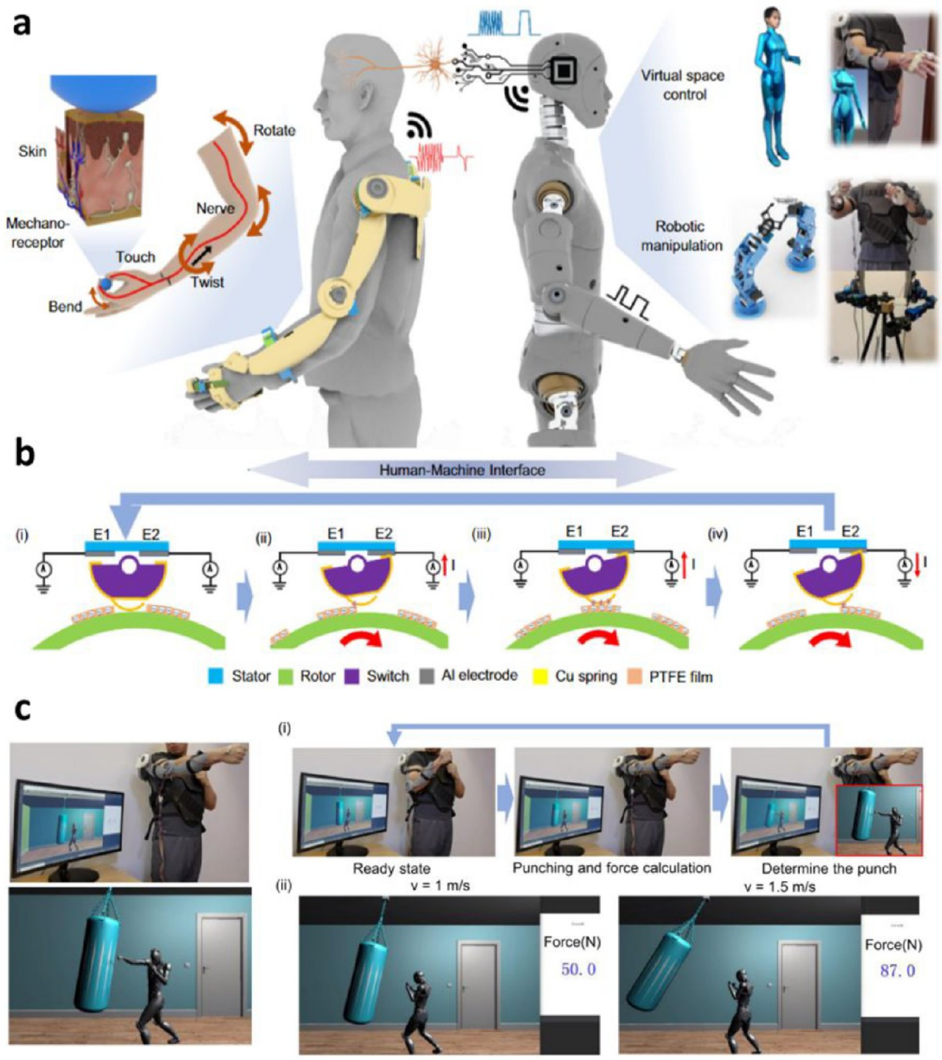

Figure 26. Grating-sliding structural TENG sensor enabled smart exoskeleton for upper-limb motion monitoring. (a) Illustration of the exoskeleton for different applications. (b) Working mechanism of the TENG sensor. (c) Demonstration of punching force estimation in VR rehabilitation application. Reprinted with permission under a Creative Commons CC BY License from ref 205. Copyright 2021 The Authors.

communication. The triboelectric sensor is operated in a sliding mode, with two Cu electrodes (*i.e.*, E-1 and E-2) encoded as "1" and "0", respectively. When a finger slides outward on the sensor surface, electrical pulses are generated on the two electrodes. Based on the pulse width and sequence, the 3-bits binary code can be decoded. For example, when the finger slides in direction 1, two pulses are consecutively generated on E-1 and E-2. Since the encoding scheme is 3 bits, which means that one of the pulses should represent 2 bits, the wider pulse from E-2 is decoded as "00" and the slimmer pulse from E-1 is decoded as "1", together forming the code "001". The photovoltaic cell in the system can continuously scavenge the ambient light energy and store it in a 0.33 F capacitor, whose voltage can reach 3 V in ∼ 230 s in an artificial light condition. The stored energy can then be used to drive the electronic circuit to send out the detected information code from the triboelectric sensor for door access or appliance control.

Next, to achieve advanced health care for the elderly and people with limited mobility, Guo *et al.* reported a self-powered and smart walking stick that is able to harvest energy from the striking actions (Figure 30).[219] Though the striking action could exert a large force on the stick, it normally has a short actuation time and low repeating frequency, which is a great challenge for energy harvesters with a resonant structure. To address this issue, a pawl-ratchet structure is designed to convert the linear striking action into low-friction rotation for effective energy harvesting. In this regard, two functional units, a rotational unit, and a hybridized unit, are fabricated and integrated into a stick. The rotational unit only consists of an EMG for energy harvesting, while the hybridized unit contains a press TENG (P-TENG), an EMG, and a rotational TENG (R-TENG) for walking habit monitoring and user recognition. To further improve the energy conversion efficiency, a power management circuit is built with a voltage amplified rectifier and an LTC3588-1 module. The managed outputs are then stored in a large capacitor (2 F) as the power supply for the wireless sensors and GPS module implemented on the stick. Thereafter, position tracking and environmental condition (temperature and humidity) sensing for the user can be achieved in a self-sustainable way, which can be sent to the

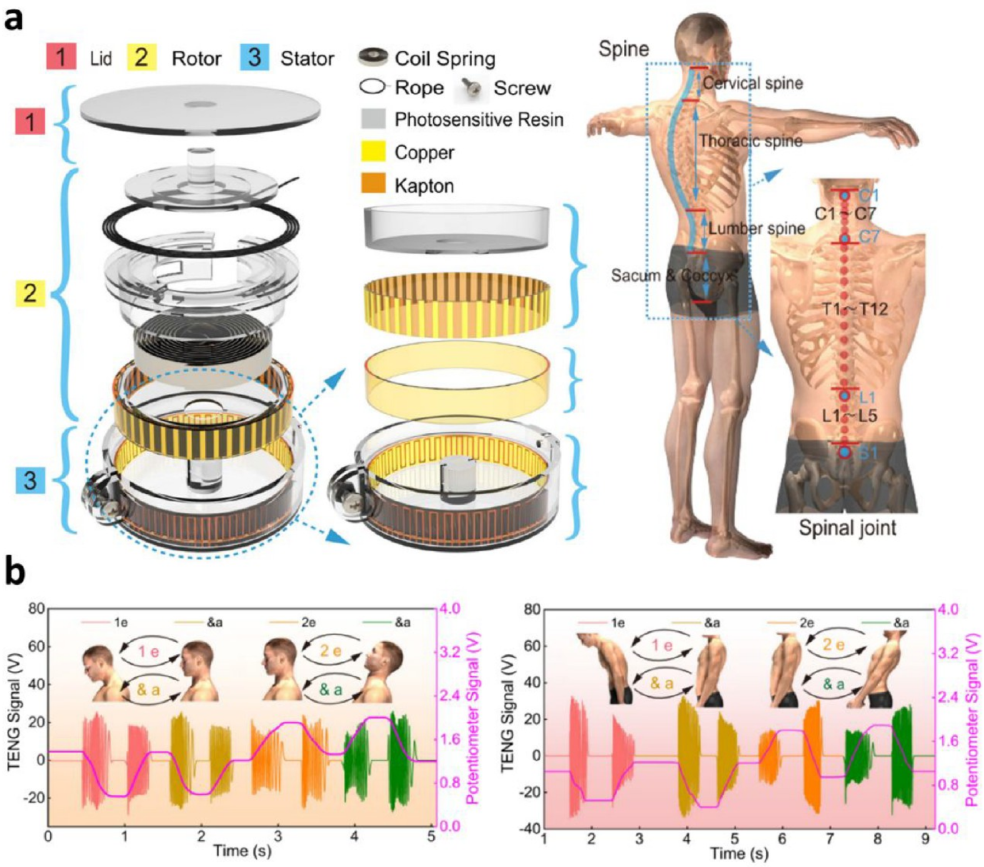

Figure 27. Badge-reel-like stretch TENG sensor to detect the spinal bending motion. (a) Enlarged view of the sensor. (b) Real-time output signals of the sensor when patients perform neck/thoracic exercises. Reprinted with permission under a Creative Commons CC BY License from ref 206. Copyright 2021 The Authors.

caregivers in real-time for more advanced health care and monitoring.

Other than the commonly adopted energy harvester integration, using zero-power sensor nodes is another promising approach to enable battery-free and self-sustained characteristics on the sensor end.[220,221] As shown in Figure 31, Wen *et al.* developed a self-powered wireless sensor network (SS-WSN) by using direct sensory signal transmission from triboelectric sensors.[222] On the sensor side, textile triboelectric sensors in contact-separation mode are integrated with a mechanical switch and a transmitting coil. The switch remains open until the maximum pressure is reached, and thus, there is no charge flow during the actuation process. Once the switch is on, all the charges are released instantaneously, and a large current is generated on the coil. Because of the capacitor-inductor configuration, an alternating electromagnetic field is then generated from the transmitting coil, with its resonant frequency dependent on the triboelectric capacitance which is further relative to the applied pressure. Therefore, the frequency of the alternating electromagnetic field contains the maximum pressure information, which offers an advantage over the conventional triboelectric sensors in terms of humidity robustness. On the receiver side, a receiving coil is utilized to acquire the transmitted electromagnetic field and demodulate the pressure information from the signals. Experimental results show that this transmission and detection scheme has high stability and high sensitivity (434.7 Hz/N) for pressure or weight sensing. In addition, by connecting different capacitors to the sensors in a mat array, a wireless control interface is realized by using only one transmitting coil, inducing a great convenience for wireless 3D drone control. Similarly, another zero-power sensor node is illustrated in Figure 32, which is a passive wireless triboelectric sensor developed by Tan *et al.* without any active electronic components like batteries or energy harvesters.[223] The key functional component for signal transmission is a surface acoustic wave resonator (SAWR), for which the resonant frequency is modulated by the pressure-sensitive triboelectric voltages *via* a tuning network (TN). To obtain the pressure information applied on the triboelectric sensor, a designed RF reader sends an interrogation signal to the SAWR and then detects its reflected response in a wireless data link. The received signals are further demodulated to extract the embedded pressure information from each communication. With a high measurement update rate of 12 kHz, continuous pressure profiles can be obtained wirelessly. In addition, the developed wireless sensor shows a large transmission range of 2 m and a high sensitivity of 23.75 kHz/V for 0−5 V triboelectric input, holding great potential to realize diverse battery-free and miniaturized sensor nodes in the IoT network.

Human activities contain abundant energy which could be a good source to realize self-sustained wearable and implantable systems.[224,225] For example, Song *et al.* reported a self-sustained sweat sensing platform by integrating a flexible freestanding TENG to harvest arm moving motions.[226] The TENG consists of a stator and a slider, both fabricated on flexible printed circuit boards (FPCBs) that can be conveniently attached to clothes. Cu is adopted as the

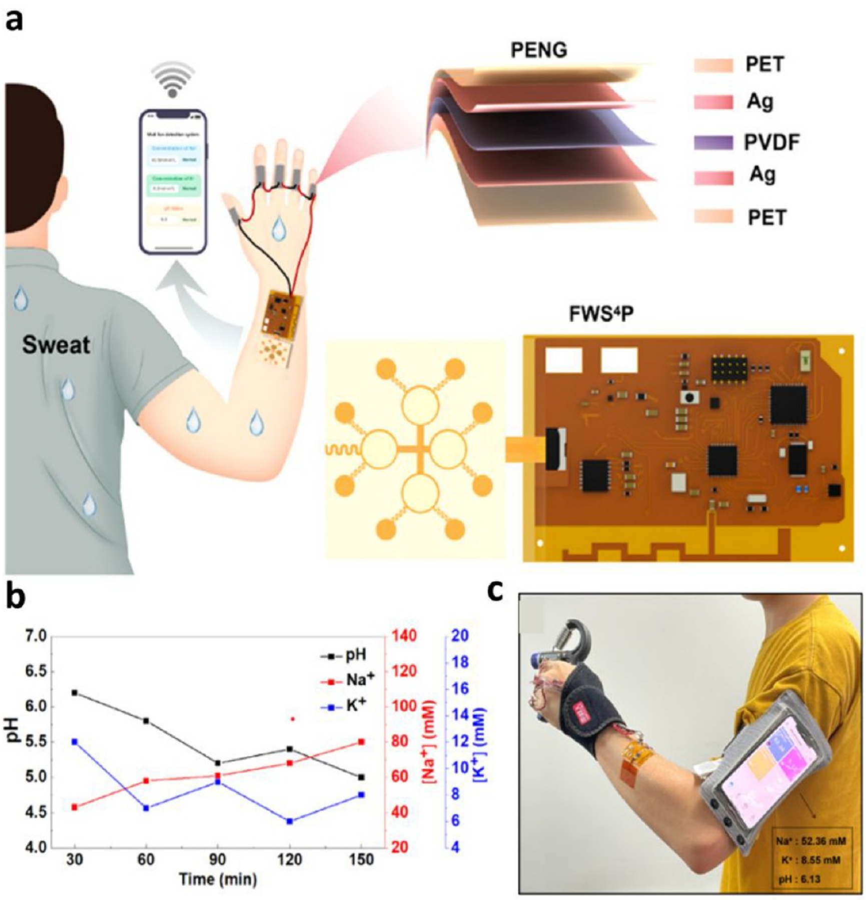

Figure 28. Self-sustainable wearable sweat sensor composed of a flexible PENG unit for energy harvesting and ion-selective electrodes for physiological parameters detection. (a) Schematic diagram of the developed sweat monitoring system. Self-powered monitoring of Na^+, K^+, and pH while (c) biking and (c) clenching. Reproduced with permission from ref 64. Copyright 2022 Elsevier.

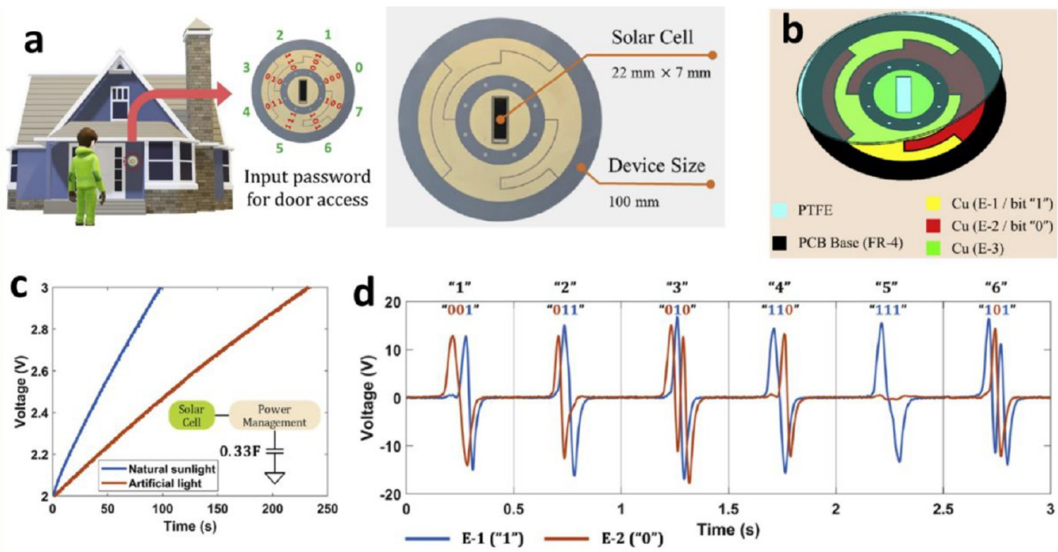

Figure 29. Self-sustained interactive system for smart-home appliance and access control. (a) Usage scenario as access password. (b) Device structure. (c) Capacitor charging by the solar cell. (d) Output signal when sliding along different directions. Reproduced with permission from ref 218. Copyright 2020 Elsevier.

electrode, and PTFE is coated on the stator as the friction material. After optimization of the comb finger width, the flexible TENG achieves a high generation performance, with a power density of ~ 416 mW/m^2 during normal activities. Then a customized power management circuit is designed for effective energy storage and output regulation. As demonstrated, the harvested energy from a user during exercise is sufficient to drive the biosensors and Bluetooth module for

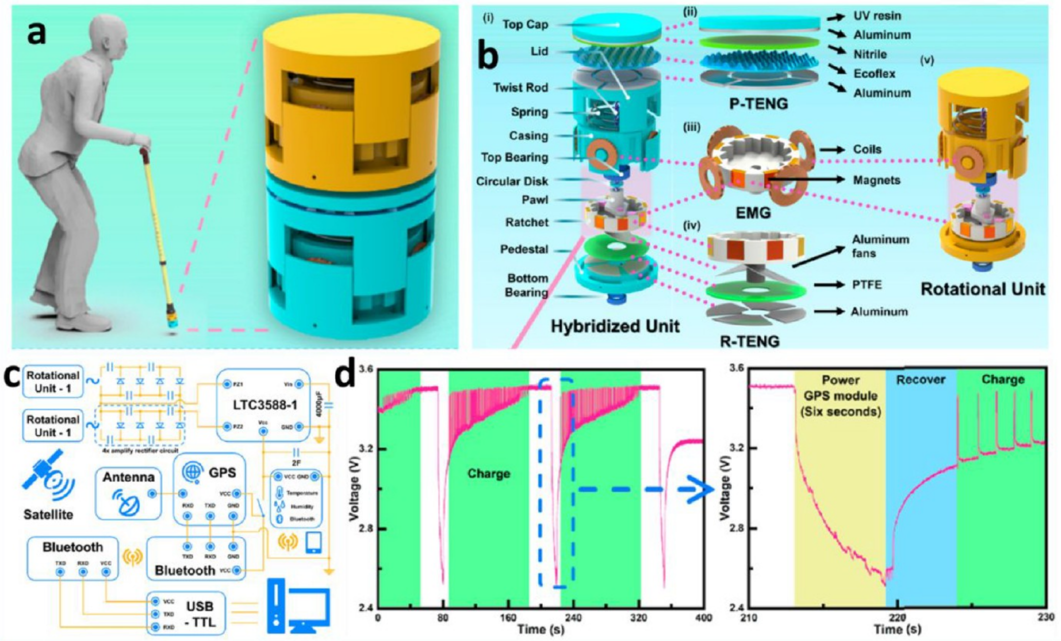

Figure 30. Self-powered and smart walking stick for position tracking and healthcare monitoring. (a) Device implementation on a stick. (b) Detailed device structure. (c) Diagram of the power management circuit. (d) Capacitor voltage during charging and discharging. Reproduced from ref 219. Copyright 2021 American Chemical Society.

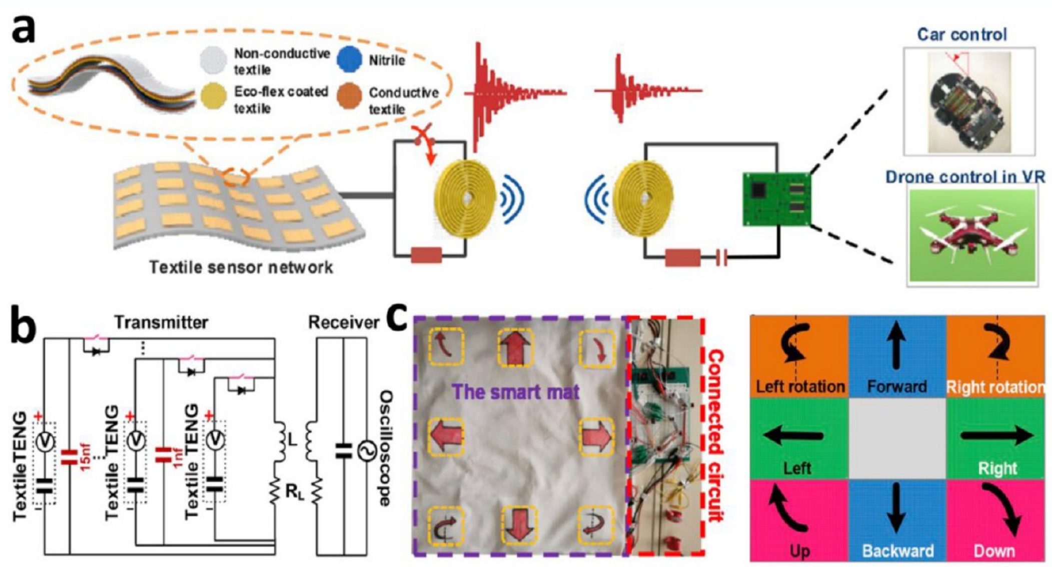

Figure 31. Self-powered wireless sensor network by using direct sensory signal transmission. (a) Overall system schematic. (b) Sensor array implementation. (c) Digital photograph and 3D drone control direction. Reproduced with permission from ref 222. Copyright 2020 Elsevier.

battery-free and intermittent (~5 min between each data transmission) sweat monitoring including the pH level and Na + concentration. Then as shown in Figure 33, Gao *et al.* designed a wireless self-powered system for lower-limb motion monitoring aiming at rehabilitation and sports training.[227] Two sliding block-rail piezoelectric generators (S-PEGs), each composed of an array of lead zirconate titanate (PZT) bimorph, are integrated to enable low-frequency energy harvesting. During a knee-bending motion, the connecting rod slides across the PZT cantilevers one by one, triggering their self-resonance with a gradual decay in amplitudes for output generation. Then two ratchet-based triboelectric nanogenerators (R-TENGs) are integrated for monitoring the bending directions and angles of lower-limb motions. The R-TENG has a rotational structure with the sensing electrode (Al) and friction material (PTFE) attached to the sidewalls. With a 15° rotation, the PET/Al on the pawl will separate from the current PTFE surface and contact the next PTFE, thus generating a pulse output for bending angle monitoring. At the system level, the generated outputs from all the PZT cantilevers will first go through independent rectifiers and then be connected in parallel for output enhancement. Next, the outputs are connected to a commercial power management chip (LTC3588-1) and a lithium battery for more effective energy storage. After that, the stored energy is used to power an Arduino Nano board to wirelessly transmit the detected

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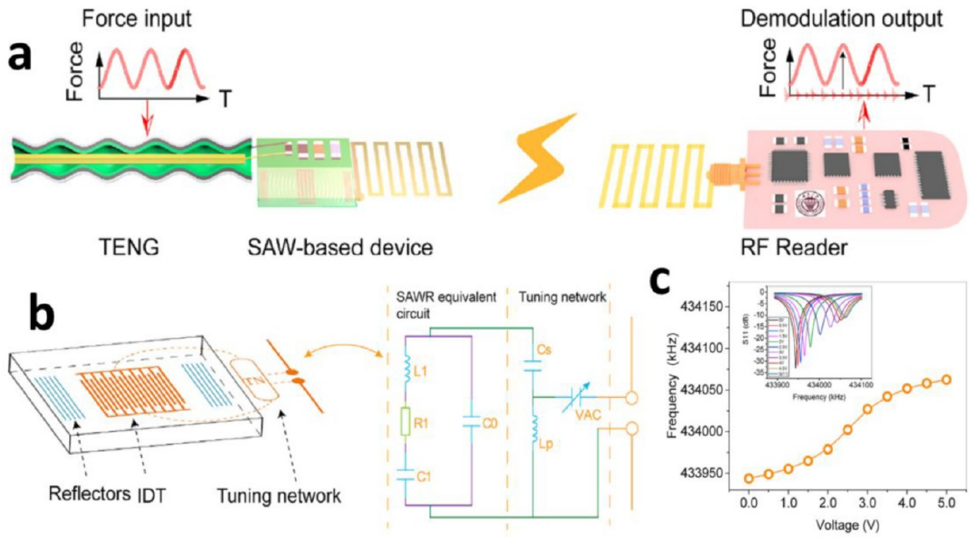

Figure 32. Totally passive wireless triboelectric sensor integrated with a SAWR. (a) System overview. (b) Equivalent circuit. (c) Frequency response with different generated voltage from the triboelectric sensor. Reproduced with permission from ref 223. Copyright 2020 Elsevier.

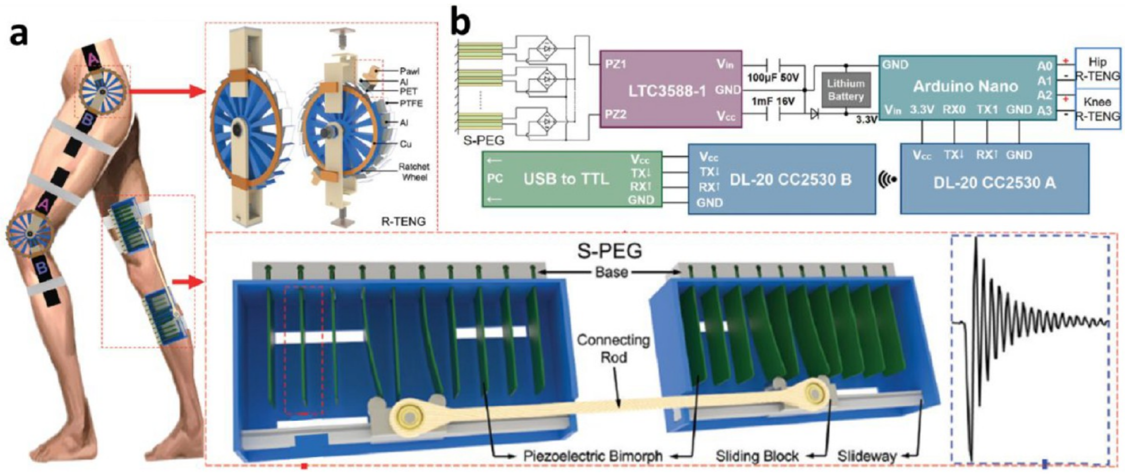

Figure 33. Wireless self-powered system for lower-limb motion monitoring. (a) Schematic of the S-PEG and R-TENG. (b) Circuit diagram of power supply and sensing. Reproduced with permission under a Creative Commons CC-BY license from ref 227. Copyright 2021 The Authors.

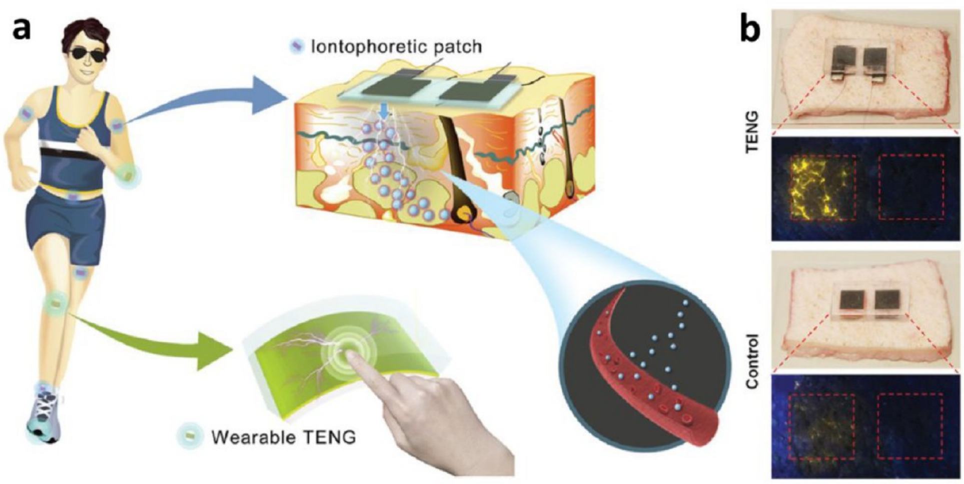

Figure 34. Wearable, closed-loop, and self-powered iontophoretic system by using the energy scavenged from human motions. (a) System overview. (b) Comparison of drug delivery results. Reproduced with permission from ref 228. Copyright 2020 John Wiley and Sons.

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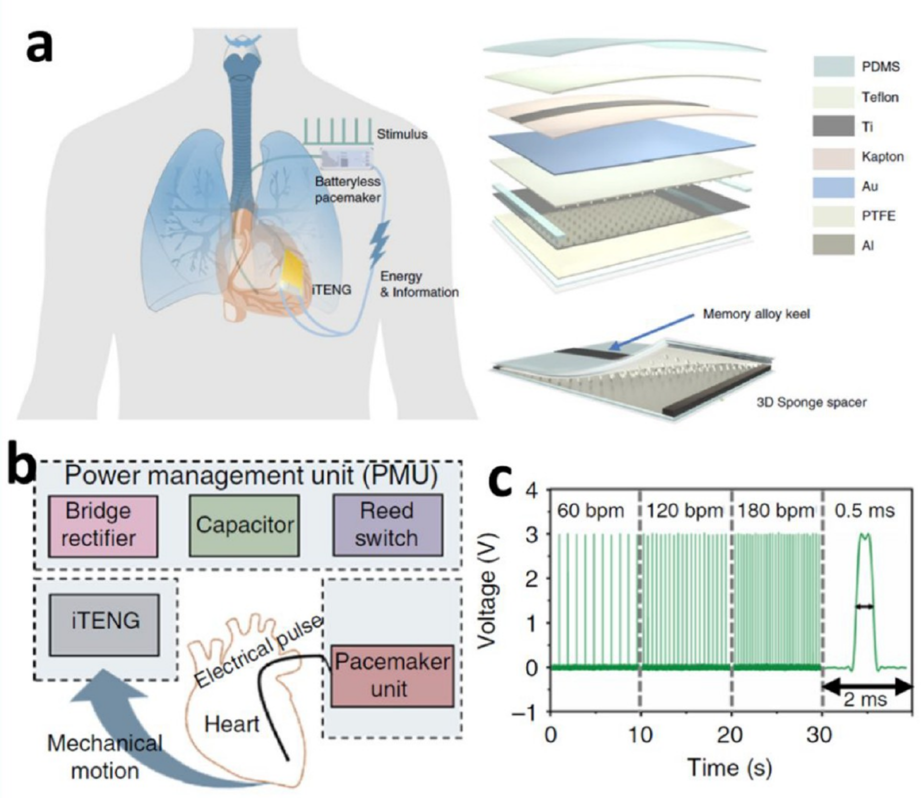

Figure 35. High-performance TENG as the power source for a fully implanted symbiotic pacemaker. (a) Device structure. (b) Diagram of the overall system. (c) Stimulation pulse of different frequencies. Reproduced with permission under a Creative Commons CC-BY license from ref 229. Copyright 2019 The Authors.

limb-bending signals from the R-TENGs for rehabilitation and training applications.

To realize a more effective transdermal drug delivery method, Wu *et al.* proposed a wearable, closed-loop, and self-powered iontophoretic system using the energy scavenged from human motions (Figure 34).[228] A wearable TENG is designed with a multilayered structure using PTFE and Al as the two triboelectric materials and is installed on the insole to convert the walking energy into electricity. Meanwhile, a hydrogel-based two-electrode patch is fabricated for non-invasive iontophoretic transdermal drug delivery. Through directly connecting the TENG outputs to the hydrogel-based drug patch, proof-of-concept experiments have been conducted on pig skins using dyes as simulated drugs. The resultant fluorescence image with TENG stimulation compared to that from a control group confirms the feasibility and effectiveness of the TENG-controlled and self-powered drug delivery system.

In implantable applications, self-sustained medical devices are highly desirable due to the time-consuming, costly, and painful surgical procedures required for battery replacements. In this regard, Ouyang *et al.* reported a high-performance and biocompatible TENG as a sustainable power source for a fully implanted symbiotic pacemaker (Figure 35).[229] The TENG utilizes both a spacer and a Ti keel supporting structure to obtain an effective separation after the external force is retrieved (such as in the case of heart contractions). A nanostructured PTFE film with corona discharging to improve the surface charge density is adopted as the negative triboelectric material. The whole device is encapsulated with Teflon and PDMS after fabrication. Through harvesting energy from the cardiac motions, the generated outputs from the implantable TENG successfully enable the symbiotic pacemaker to correct sinus arrhythmia and prevent deterioration. Upon each cardiac motion cycle, the implantable device can produce 0.495 μJ of energy, higher than the threshold energy needed for endocardial pacing (0.377 μJ). With the promising output performance, the proposed TENG exhibits great potential in powering implantable symbiotic bioelectronics. Thus, we can envision more implanted medical devices powered by implantable energy harvesters in the near future.

7. AIoT SYSTEMS

The rapid development of AI in recent years paves the way for enhancing sensor functionalities by automatically extracting key information from the sensor output signals to realize advanced applications, *e.g.*, human/object identification, gesture recognition, voice recognition, *etc.*[230−232] The recent progress of the IoT has also provided a foundation for the establishment of distributed sensor networks in smart homes,[233,234] which can be further integrated with AI technology toward AIoT-enabled living environments, offering people with more convenient human−machine interactions, enhanced home security, and comprehensive indoor activities and health monitoring in daily life. In this regard, there is an increasing trend in the development of assistive physical therapy devices in smart homes, especially those with AI-aided functionalities and self-powered sensing capabilities.[235] Different from the current mature AI techniques based on the visual sensory information that usually has high complexity and needs relatively more complicated algorithms, such as the visual geometry group (VGG) and residual network (ResNet), the

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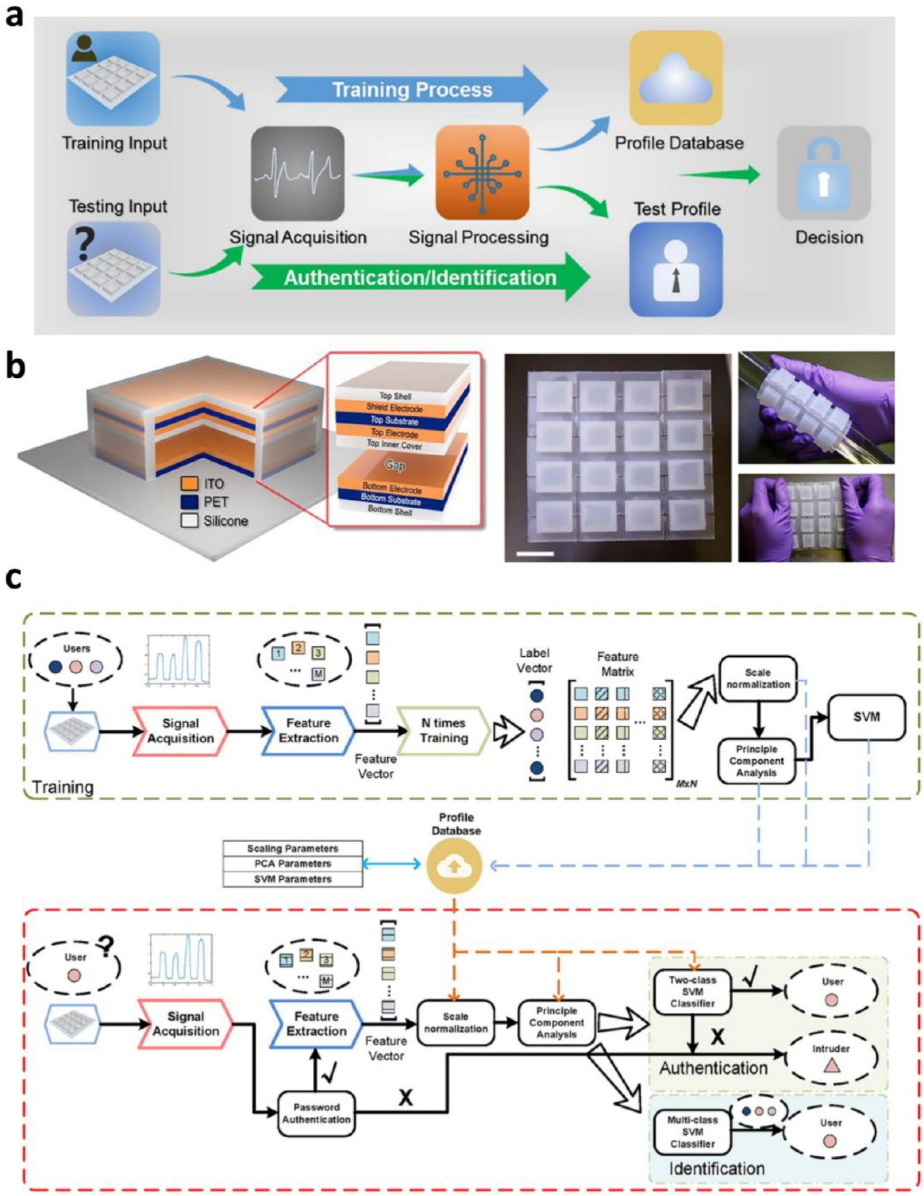

Figure 36. TENG sensor enabled smart keyboard for biometric authentication applications in smart homes. (a) Diagram of the keystroke dynamics enabled authentication system. (b) Illustration of the structure of the TENG key. (c) Training and identification of the system based on the SVM algorithm. Reproduced with permission from ref 16. Copyright 2018 Elsevier.

output complexity from such nonvisual sensors and HMIs is significantly reduced and could be processed well by some lightweight algorithms, *e.g.*, support vector machine (SVM), one-dimensional convolutional neural network (1D-CNN), *etc.*, to greatly lower the computational cost of the entire system.

The internet has penetrated every corner of our life, where the network security has become a common concern. In terms of this issue, keystroke dynamics-based security systems have been proven as a feasible way to enable a higher security level based on people's unique typing attributes.[158,236] As shown in Figure 36, Wu *et al.* developed a two-factor, pressure-enhanced key security system, which can verify and even identify users through their specific typing behavior.[16] Due to the unique contact-separation-mode TENG-based keys, this smart keyboard shows the merits of self-power supply, scalability, and high mobility. The silicone shell allows the device to be comfortable for daily use, and the shield electrodes are used to reduce the noise from inadvertent touch or environmental interference. By using principal component analysis (PCA) for feature dimensionality reduction, and an SVM for further classification, high identification accuracy of 98.7% could be achieved for 5 users according to their different keystroke-related features, *i.e.*, typing latencies, hold time, and signal magnitudes, demonstrating the great significance of keystroke dynamics to protect user information in smart homes or even financial industry scenarios.

As another common HMI in our life, microphones could also be used for biometric applications by analyzing a user's specific voiceprints with the help of AI technology.[168,237] Compared with the conventional ML methods using k-nearest neighbors (KNN) or SVM, DL approaches using neural networks are capable of extracting the fine features automatically, which may contribute more useful sensory information to

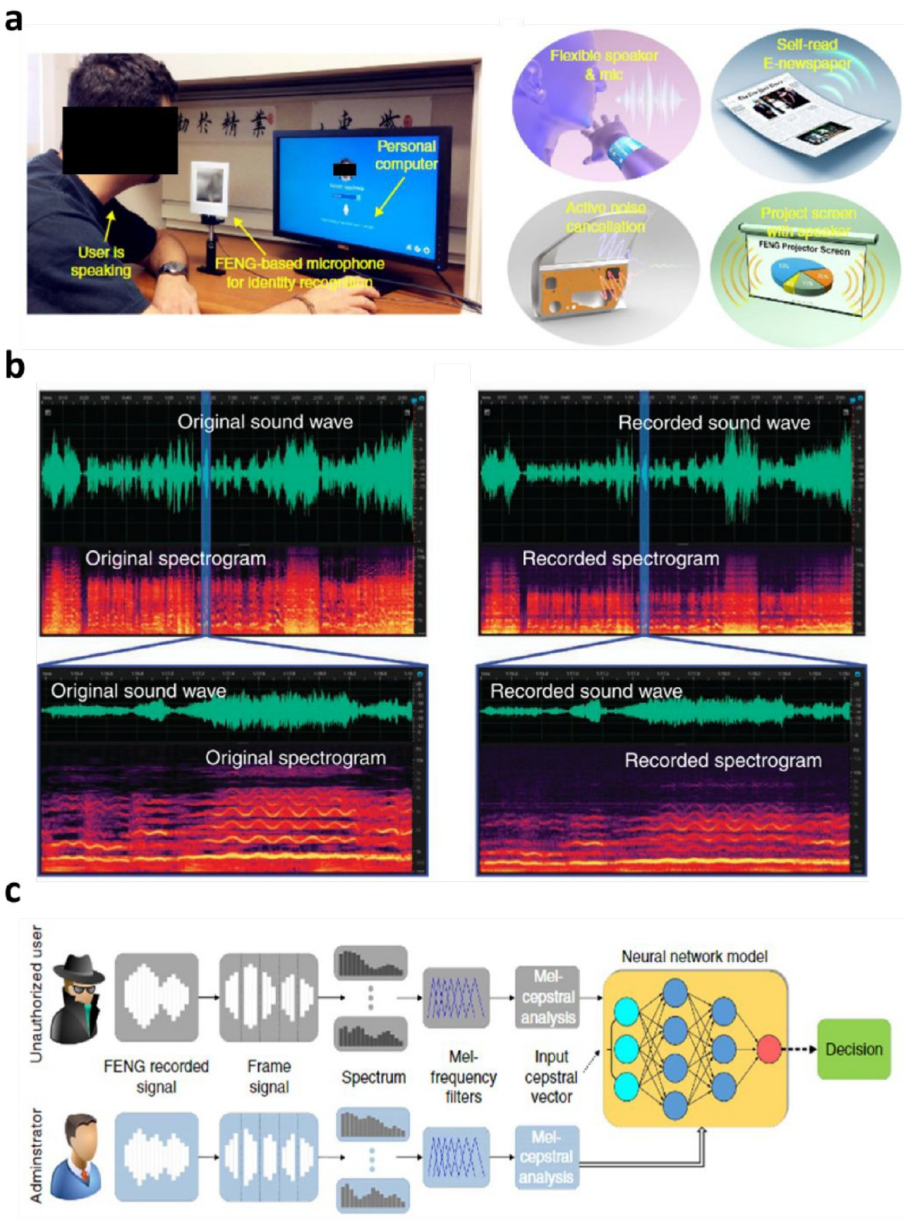

Figure 37. Self-powered thin-film flexible microphone based on ferroelectric nanogenerator (FENG) for authentication purpose in the smart home. (a) FENG-based identity recognition system. (b) Acoustic wave recording using the FENG-based microphone. (c) neural network model for real-time identification. Reprinted with permission under a Creative Commons CC BY License from ref 238. Copyright 2017 The Authors.

enable better identification performance. As illustrated in Figure 37, Li *et al.* proposed a self-powered thin-film flexible microphone based on a ferroelectric nanogenerator (FENG) for authentication purposes.[238] By leveraging microplasma discharging, the artificial voids inside the foam-structured FENG form numerous giant dipoles, enabling the FENG with outstanding electromechanical transformation efficiency and a broad frequency sensing range. Different from the traditional security method based on the text password which may be easily hacked, the FENG-enabled microphone security system uses both the text password and the authorized user's biometric information, *i.e.*, voice, which enables an extra security layer. By using an artificial neural network model to analyze the voiceprint of users, an individual's discrepancy of the physical shape of the vocal tract could be easily differentiated by the authentication system based on the key information hidden in the acoustic waveform, *i.e.*, time-domain/frequency-domain acoustic information and acoustic energy information. Afterward, access is given to the authentic users whose voiceprints already existed in the saved database.

Besides the keystroke dynamics and voiceprint, it is also feasible to realize a biometric authentication system for smart homes based on gait-related information,[239,240] which could be captured by a sock- or floor-based sensory system. Zhang *et al.* developed intelligent TENG socks enabled by DL technology as shown in Figure 38.[97] Three textile-based TENG pressure sensors with high sensitivity (0.4 V /kPa) are fabricated and embedded on the sock for gait signal collection. Each TENG sensor consists of four layers: a silicone rubber film with pyramid structures as the negative triboelectric layer, a nitrile thin film as the positive triboelectric layer, and two conductive textiles as the output electrodes. All layers are packaged with

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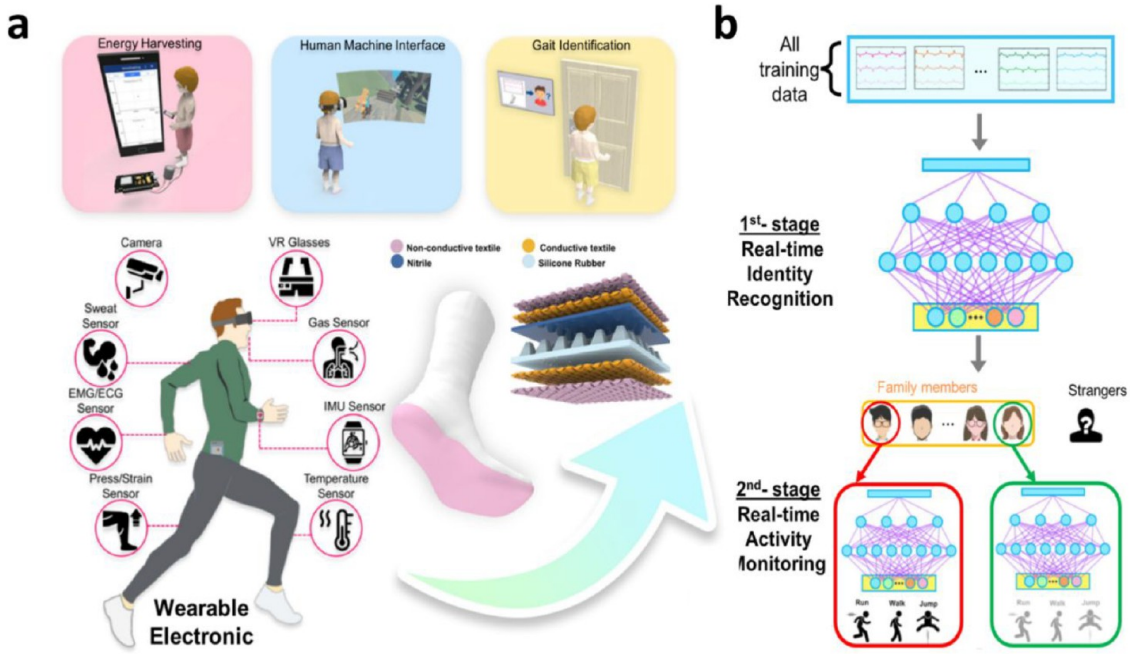

Figure 38. Intelligent TENG socks enabled by deep learning technology for indoor gait data collection and analysis. (a) Schematics and applications of the smart TENG socks. (b) Two-stage recognition system for smart home applications. Reprinted with permission under a Creative Commons CC BY License from ref 97. Copyright 2020 The Authors.

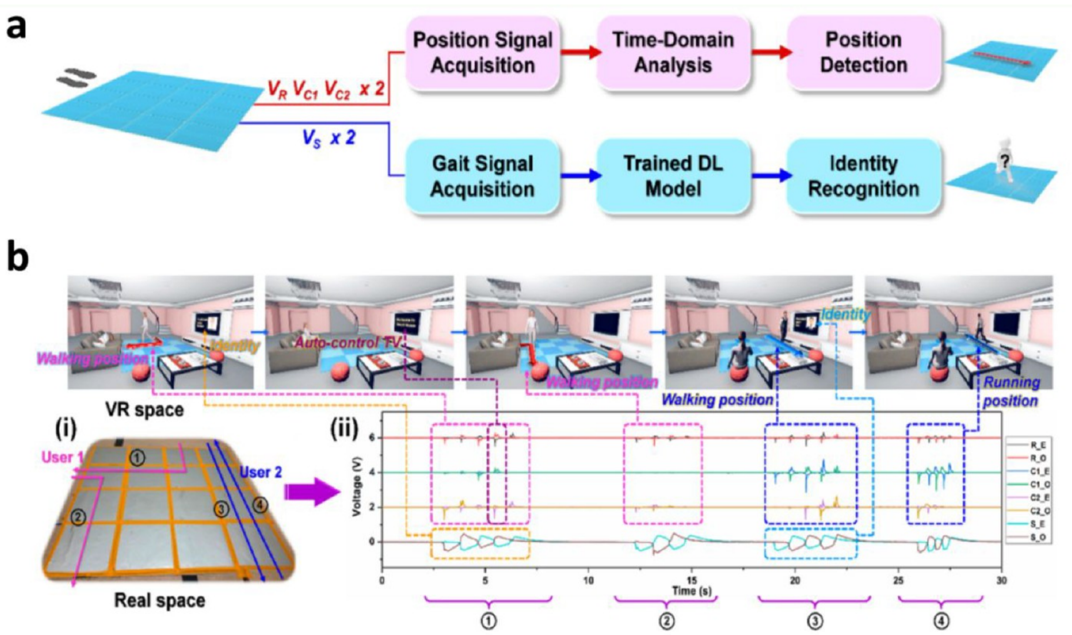

Figure 39. Triboelectric sensor embedded smart floor enabled multifunctional monitoring system in smart homes. (a) Diagram of the smart floor for position detection and identity recognition. (b) Demonstration of the floor for tracking and identifying two users simultaneously. Reproduced from ref 241. Copyright 2021 American Chemical Society.

nonconductive textiles and further sewn onto the cotton socks for daily use. Due to the space variation between two triboelectric layers caused by the pressure-induced pyramid deformation, gait patterns could be easily transformed into electrical signals. By leveraging 1D-CNN, a proven effective DL algorithm for dealing with the time-domain signals of physical sensors, for data analysis, a smart home system was successfully developed, where the identity recognition (93.54% accuracy of 13 participants) and the real-time indoor activity monitoring (96.67% for 5 activities) could be achieved simultaneously in a no-camera environment for privacy and security purpose. As illustrated in Figure 39, Shi *et al.* developed a triboelectric sensor embedded smart floor through the cooperative integration of an advanced coding-electrode design, ratio-based measuring scheme, and DL analytics.[241] In this work, a PET thin film as a well-established material in the screen-printing process with good triboelectric positivity and chemical resistance is utilized for large-scale manufacturing.

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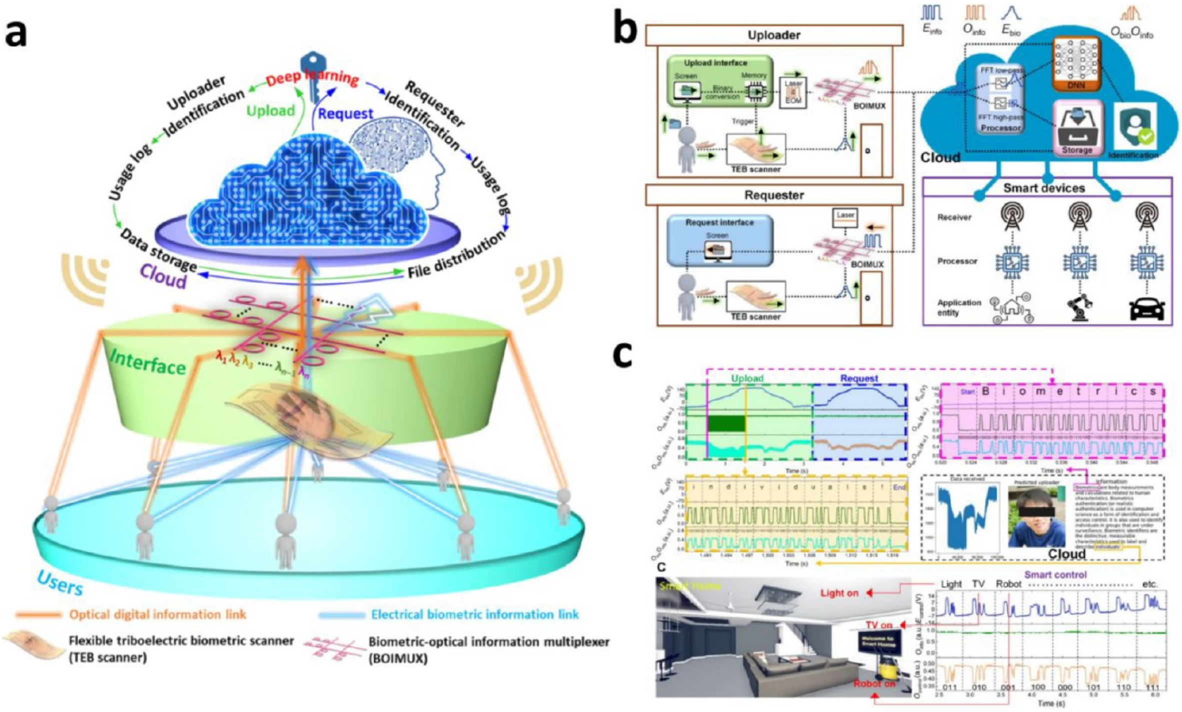

Figure 40. DL-enhanced triboelectric/photonic synergistic interface for the secure data access in the cloud server. (a) Architecture of the biometrics-protected optical communication. (b) Operation principle of the system. (c) Upload and request waveforms and the developed interface. Reprinted with permission under a Creative Commons CC BY License from ref 242. Copyright 2022 The Authors.

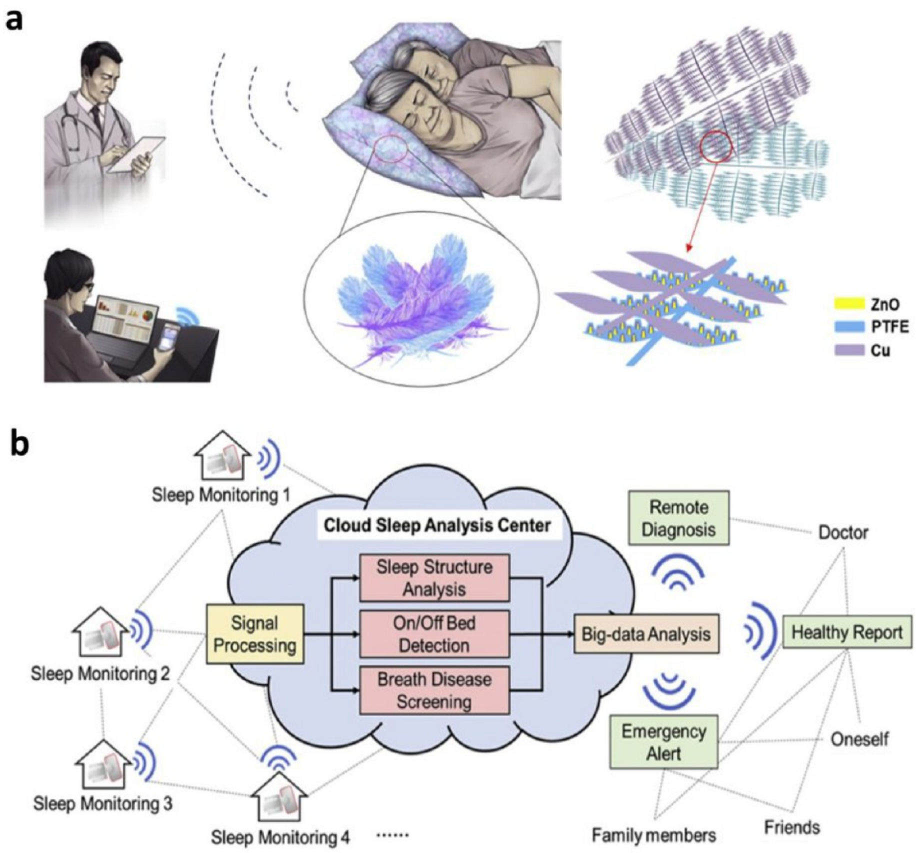

Figure 41. Advanced wireless sleep monitoring bedding enabled by a self-powered triboelectric body-motion sensor. (a) Illustration of the pillow filled with TENG sensors for sleep monitoring. (b) System diagram of the cloud sleep analysis system. Reproduced with permission from ref 245. Copyright 2020 Elsevier.

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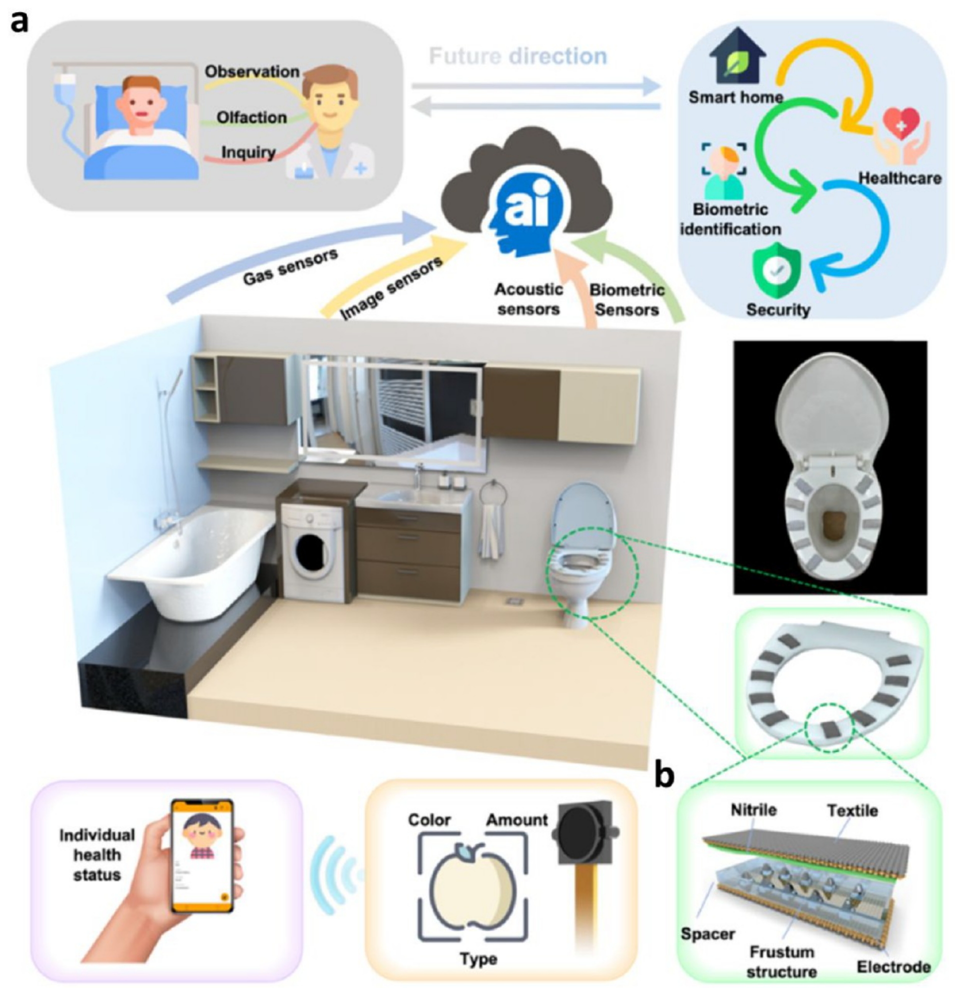

Figure 42. AI-Toilet by fusing the triboelectric and image sensing technology. (a) Schematic of the AIoT enabled toilet for health monitoring. (b) Detailed structure of the TENG sensor. Reproduced with permission from ref 248. Copyright 2021 Elsevier.

Then the coding electrodes are configured and printed on top with quaternary coding schemes only through external wiring, so that only one mask is needed during the fabrication process for cost-effectiveness. Different from previous floor mats based on the output amplitudes, the outputs of this sensing system are normalized with that from a reference electrode, and thus, detection is not affected by the environment and highly stable detection data are obtained. With the 1D-CNN analytic for gait feature extraction, a recognition accuracy of around 85% could be achieved for 20 users, which is sufficient for most smart home scenarios. Moreover, the functions of irregular trajectory and multiuser detection could be realized by slightly adjusting the electrode connections, showing its great potential to develop a multifunctional monitoring system for smart homes in the era of IoT.

The above-mentioned authentication systems are all based on the time-domain signals from physical sensors, where many analog-to-digital and digital-to-analog conversions are needed during the signal collection and processing procedure, greatly affecting the transmission efficiency. In terms of this issue, loading and transmitting time-domain signals in optical format could be advantageous considering the ultrahigh transmission speed and simplified signal processing. In addition, by leveraging the multisensor synergizing strategy to enable data multiplexing, the internet and communication security in smart homes could be enhanced to a higher level. As shown in Figure 40, Dong *et al.* proposed a DL-enhanced triboelectric/photonic synergistic interface for secure data access in the cloud server.[242] The low-frequency biometric data and the control information could be collected by the TENG-based tactile sensing unit and transferred into optical domain with minimized power consumption. Meanwhile, the high-frequency digital information (such as text or video data) could be multiplexed with the biometric information in the optical domain, in order to enhance the data complexity and security without disrupting the original data transmission. In the cloud end, the multiplexed data could be further demultiplexed to recover the protected information after the user identification process enabled by the 1D-CNN data analytic (~95% accuracy for 15 users). As a result, secure communication between users and the cloud can be realized for document exchange and smart control purposes in the smart home environment.

In this fast-paced era, more and more people suffer from sleeping disorders, which may also result in other serious health problems, *e.g.*, depression, cancer, heart disease, *etc.* Though the big-data-enabled sleep analysis is helpful for early diagnosis, the current monitoring technologies are limited since most of them are uncomfortable for long-term daily use.[243,244] To address this issue, Zhang *et al.* proposed an advanced wireless sleep monitoring bedding enabled by a self-

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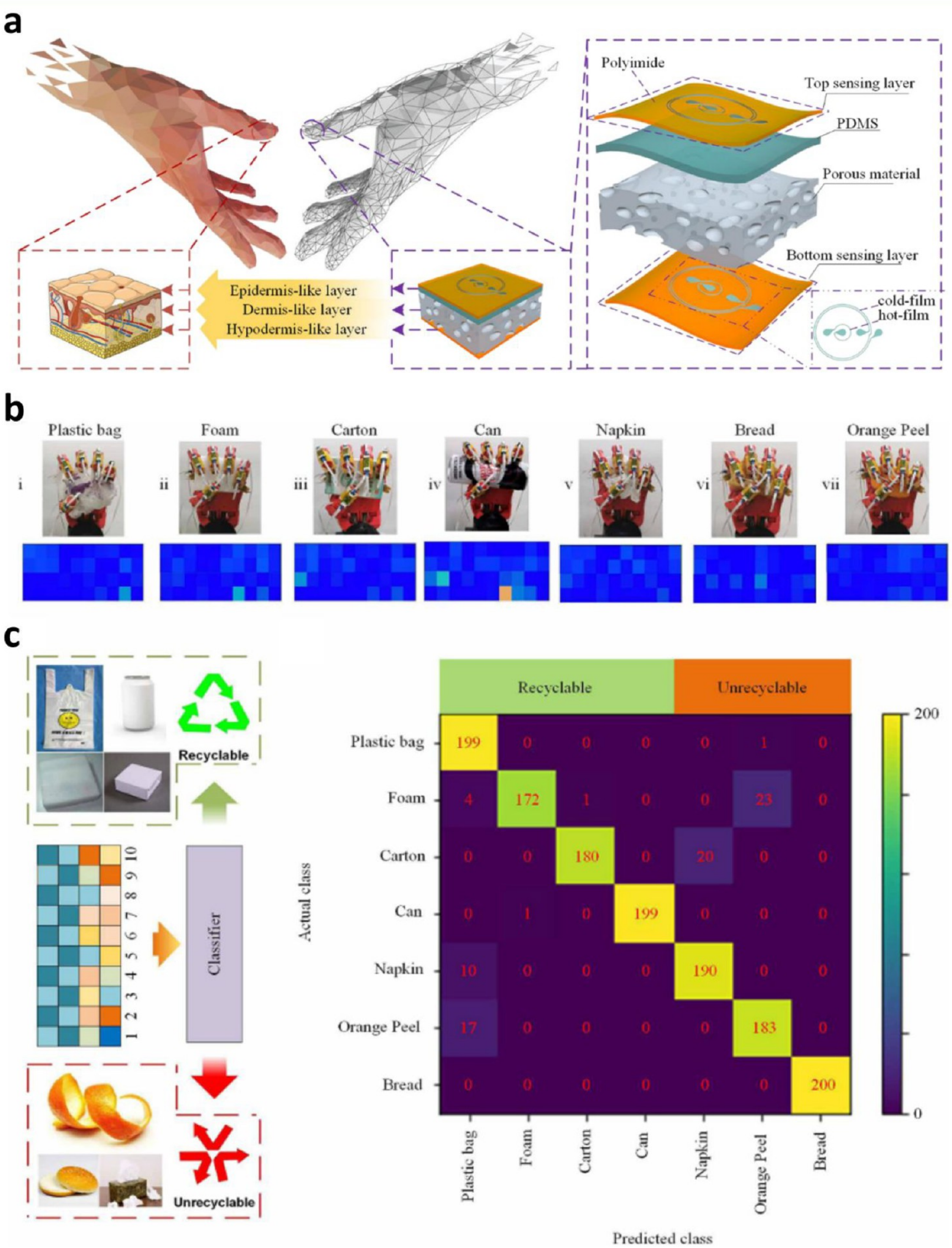

Figure 43. Flexible quadruple tactile sensor for robot perception applications in smart homes. (a) Skin-inspired multilayer structure of a quadruple tactile sensor. (b) Signal maps for grasping different objects. (c) Garbage sorting system based on the tactile sensor. Reproduced with permission from ref 251. Copyright 2020 The American Association for the Advancement of Science.

powered triboelectric body-motion sensor as shown in Figure 41.[245] The TENGs are designed with a highly sensitive and reliable fractal pile structure, which could be stuffed into the pillow for various locomotive activities monitoring, including breathing, turning-over, mild/severe snoring, *etc.*, according to their specific output waveforms. With the wireless IoT framework for data transmission, sleep structure analysis, on/off bed detection, and breath disease screening could be achieved simultaneously by AI-enabled big-data analytics. Then a comfortable remote sleep healthcare and diagnosis system could be established with credible sleep-stage estimation results that are quite close to those from professional polysomnography, providing a reliable way to

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realize sleep monitoring for the elderly at home to reduce the chance of sudden death during sleep to a certain extent.

Another possible solution to enrich the smart home monitoring system is to collect the diagnostic information of urine and stool,[246,247] which are the main byproducts of human systems and may contain a lot of valuable information related to the health conditions of individuals. Zhang *et al.* reported an AI-Toilet by fusing the triboelectric and image sensing technology as depicted in Figure 42, which provides a feasible platform for long-term analysis of human health.[248] The TENG sensor utilized in this integrated system is textile-based with embedded nitrile and silicone rubber thin films serving as the triboelectric layers, enabling good softness and comfort in contact with human skin. The 10-pixel triboelectric pressure sensor array can obtain biometric information by analyzing the seating methods of individual users with different pressure distributions, where an accuracy of greater than 90% could be obtained for six users by leveraging the 1D-CNN analytics. The image sensing system can analyze the urine by referring to a urine chart and classify the type and quantity of objects by a 2D-CNN model (accuracy of 97% and 91% for four stools and stool amounts, respectively). All of the health-related information could be obtained by the integrated powerful AIoT system, uploaded to the server, and further displayed on the user's mobile device for continuous health monitoring and valuable clinical information.

With the development of AI and robotics technology, intelligent robots equipped with advanced sensors and self-discrimination capabilities are certainly an indispensable part of future AIoT-enabled smart homes to help ease people's burden of housework.[249,250] As depicted in Figure 43, Li *et al.* successfully developed a flexible quadruple tactile sensor to let the robot hand perceive grasped objects of different materials and shapes, and further use a multilayer perceptron (MLP) algorithm that contains three hidden layers to realize automatic garbage classification.[251] The tactile sensor consists of two sensing layers sandwiching a porous silver nanoparticle-doped PDMS, where each sensing layer is made up of two sensing elements, *i.e.*, hot and cold film, that are concentric annular Cr/Pt. The top and bottom hot films respond to the thermal conductivity of the contact object and the applied pressure respectively based on the difference in thermal conductivity of different materials and deformation-induced thermal conductivity change of porous material. The cold films serve as local temperature sensors to detect the object and environmental temperatures. The developed tactile sensor can perceive multiple stimuli simultaneously without obvious cross-coupling errors, which can provide more useful features related to the objects and effectively improve the recognition accuracy during the ML process. After mounting the sensors on a robot hand, an intelligent garbage sorting system was successfully achieved, where the identification accuracy of seven types of recyclable/unrecyclable garbage could be greater than 94% with the simple three-layer neural network, showing its feasibility to greatly ease people's burden for environmental protection and sustainable development in smart homes.

8. CONCLUSIONS AND OUTLOOK

In summary, we have systematically reviewed the recent progress of the rapid development of advanced materials, fabrication techniques, functional devices, and systems for enabling diversified smart home and health care applications. In particular, advancements in highly stretchable, biocompatible, and self-healing polymers as well as air-permeable fabrics and textiles have been discussed toward the application of more comfortable, convenient, and long-term monitoring. Meanwhile, large-scale fabrication techniques such as spray-coating, roll-to-roll printing, screen printing, electrospinning, braiding, and weaving/knitting have also been presented for large-area applications in smart homes, *e.g.*, floor sensors, bed sensors, and whole body sensors. In the aspect of ambient devices and wearable devices that are deployed at the various locations of home ambiance and human body, we have reviewed in detail their design considerations, working mechanisms, and application scenarios, such as motion tracking, environment monitoring, intelligent interaction, health care, rehabilitation, automation, assistance, and security. Along with the prompt technology innovation, self-sustained systems and intelligent systems have received tremendous research efforts and thus are presented as two promising development trends to suffice the increasing demands of future smart homes.

Though with the significant achievements so far, there are still some existing challenges as well as research opportunities for future development in order to realize a fully connected, self-sustained, and intelligent smart home platform. First of all, the current energy supply based on energy harvesters can only support the operation of low-power systems, mostly in intermittent mode, which means a generally long charging period is needed before the actual operation. For systems with moderate or large power consumption, such as remote and wireless systems, the charging period is even longer. In this regard, long-range and real-time wireless communications in between systems and the cloud server are greatly restricted to enable fully connected and rapid-response smart home systems. Hence, the energy harvesting efficiency of current generators needs to be further optimized in order to extract the most out of the ambient energy sources. One possible approach is integrating several transducing mechanisms to form hybrid energy harvesters, with synergic effects to improve the overall efficiency and adaptability.[252] In addition, effective power management circuits and energy storage units are also important and should be considered while optimizing the energy harvesters from the system point of view.[253] Next, with more and more sensors deployed in smart homes, sensory information and data in different formats are continuously generated. Thus, how to effectively perform information fusion and data analytics of these multimodal signals will be crucial to enable real-time monitoring and response systems. In addition, wireless communication consumes most of the power required, and thus, edge computing could be more efficient in terms of energy saving when massive amounts of data need to be transmitted. But in conformity with the self-sustained systems, whether the harvested energy is sufficient for edge computing will require further investigations. Last but not least, how to seamlessly combine various functional components such as sensors, energy harvesters, actuators, circuits, supercapacitors/batteries, wireless modules, computing units, *etc.* into an integrated system should be carefully considered. As for the wearable and implantable applications, stretchable skinlike electronics are more preferred but certain components could be rigid and bulky. After individual device optimization, system-level design and optimization should then be performed to achieve better performance and functionality. All in all, with the continuous technology innovations, we can

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envision the realization of an all-in-one, fully connected, self-sustained, and AI-enabled smart home platform in the future.

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Author Contributions

C.L. supervised the project. Q.S. and C.L. conceived the review concept and flow. Q.S., Y.Y., and Z.S. drafted the manuscript. All the authors contributed to the preparation of the manuscript.

Notes

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