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Triboelectric nanogenerators as self-powered sensors for biometric authentication

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As a prerequisite for ensuring the safety and stability of people's daily lives, security monitoring has become increasingly important in the current rapid development of the economy. Intelligent sensing technology with lower power consumption will promote the upgradation of electronic devices and expand new application requirements. In this review, the recent progress in triboelectric nanogenerators (TENGs) as self-powered intelligent sensors for monitoring different kinds of biometric characteristics is summarized, including sliding behavior, handwriting behavior, keystroke dynamics, gait characteristics, and voice characteristics. Additionally, the applications of self-powered systems based on TENGs in individual electronics authentication and home security are comprehensively summarized. Finally, the remaining challenges and open opportunities are also discussed.

1. Introduction

With the rapid development of the Internet of Things (IoT),[1,2] artificial intelligence,[3–5] and cloud computing,[6,7] security monitoring has become more and more important in protecting people's property and life.[8–10] Biometric authentication is an automatic method that verifies or identifies the user depending on the detection of unique physiological traits such as the iris, fingerprint, and face, or behavioral traits such as gait, handwriting, and keystroke dynamics.[11,12] It can offer a convenient, effective, and reliable solution to recognize the user's identity. Recently, biometric identification technology based on a variety of behavioral characteristics has been

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attracting increasing attention and has been extensively used in the security domain.[13] However, the acquisition of the security monitoring data relies on extensively distributed sensors, which are usually powered by traditional energy storage devices, such as batteries. Considering their high replacement costs, limited lifetime, and environmental issues, it is highly desirable to develop a maintenance-free and sustainable sensing technique.

Based on the coupling effect of contact electrification (CE) and electrostatic induction, triboelectric nanogenerators (TENGs) have recently been developed as promising technology to convert irregular, distributed, and low-frequency mechanical energy into electrical energy.[14–16] Benefitting from the unique merits of low cost, simple structure, high efficiency, and versatile choices of materials,[17–19] TENGs are able to harvest electricity from a variety of mechanical energy sources in the external environment for realizing large-scale self-powered electronic networks.[20–24] In addition, TENGs can also be utilized as self-powered sensors by directly converting mechanical stimuli to electrical signals, which is significant for the development of maintenance-free and sustainable security monitoring systems.[25–30] Considering the high replacement costs, limited lifetime, and environmental pollution of conventional electronics, TENG technology will have a wide range of application prospects in the field of smart security systems, where a large number of IoT devices should be used.

Here, the recent advances and practical applications of TENG-based intelligent sensors for biometric authentication are comprehensively summarized. According to the difference in recognition features, the application areas of self-powered sensors are classified into five major parts, including sliding behavior, handwriting behavior, keystroke dynamics, gait characteristics, and voice characteristics (Fig. 1). Additionally, the applications of TENG-based self-powered systems in individual electronic authentication and home security are also discussed. At the end, some challenges for the future development of TENG-based self-powered sensors in biometric authentication are discussed. We expect that this review will not only give a summary of the current research situation, but also provide a reference for future research on high-performance intelligent TENG-based self-powered security systems.

2. Fundamental theory of TENGs

As a common and ancient phenomenon, the triboelectric effect has been known for more than 2600 years, and it exists everywhere and anytime in our daily life. However, it is usually regarded as a negative effect that should be avoided and eliminated in people's daily life. In 2012, based on the coupling effect of CE and electrostatic induction, this effect was first applied to develop TENGs as a new mechanical energy harvesting and self-powered sensing technology by Wang and coworkers.[14] Generally, physical contact between two different dielectric materials will cause triboelectric charges on the two contacted surfaces. Then, the relative separation and/or sliding between the two contacted surfaces can result in a potential difference, which drives the electrons to flow between the two electrodes in order to balance the electrostatic system. As CE can occur between all phases, studying its fundamental mechanism plays a significant role in the development of chemistry, physics, and biology.

Recently, Wang and co-workers found that electron transfer is the dominant mechanism for CE in solid-solid cases.[16] An atomic-scale electron cloud-potential well model is proposed to explain the CE-induced electricity generation mechanism of TENGs. The repulsive and attractive interactions between atoms can be understood from the interatomic interaction potential. Additionally, mechanical pressure has to be applied to shorten the interatomic distance and cause the overlap of the electron cloud.[41,42] This model is considered a universal model to understand CE between any two materials, and can be extended to other cases of CE.

As one of the top ten most important equations in physics, Maxwell's equations are the foundation of modern photonics, wireless communication, light communication, and many more.[43] One of the greatest creative ideas by Maxwell in 1861 was the introduction of displacement current in Ampere's law, which resulted in the unification of electricity and magnetism. Recently, considering the contribution of electrostatic charges caused by contact electrification, the expression of displacement current has been expanded.[15] An additional term $\boldsymbol{P}_\mathrm{S}$ was added to the displacement vector D, that is

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} + \boldsymbol{P}_\mathrm{S} \tag{1}$$

where $\boldsymbol{P}_\mathrm{S}$ is caused by the polarization field generated by the surface electrostatic charges, which are independent of the electric field. By defining a new vector $\boldsymbol{D}'$, where $\boldsymbol{D}' = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}$, the expanded Maxwell's equations can be reformulated as

$$\nabla \cdot \boldsymbol{D}' = \rho' \tag{2}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{3}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{4}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}' + \frac{\partial \boldsymbol{D}'}{\partial \boldsymbol{t}} \tag{5}$$

where the volume charge density and the current density can be redefined as

$$\rho' = \rho - \nabla \cdot \boldsymbol{P}_\mathrm{S} \tag{6}$$

$$\boldsymbol{J}' = \boldsymbol{J} + \nabla \cdot \frac{\partial \boldsymbol{P}_\mathrm{s}}{\partial t} \tag{7}$$

According to the above equations, the total Maxwell displacement current can be revised as

$$J_\mathrm{D} = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_\mathrm{s}}{\partial t} \tag{8}$$

Here, the first term $\varepsilon \frac{\partial \boldsymbol{E}}{\partial t}$ represents the displacement current caused by the changing electric field and the electri-

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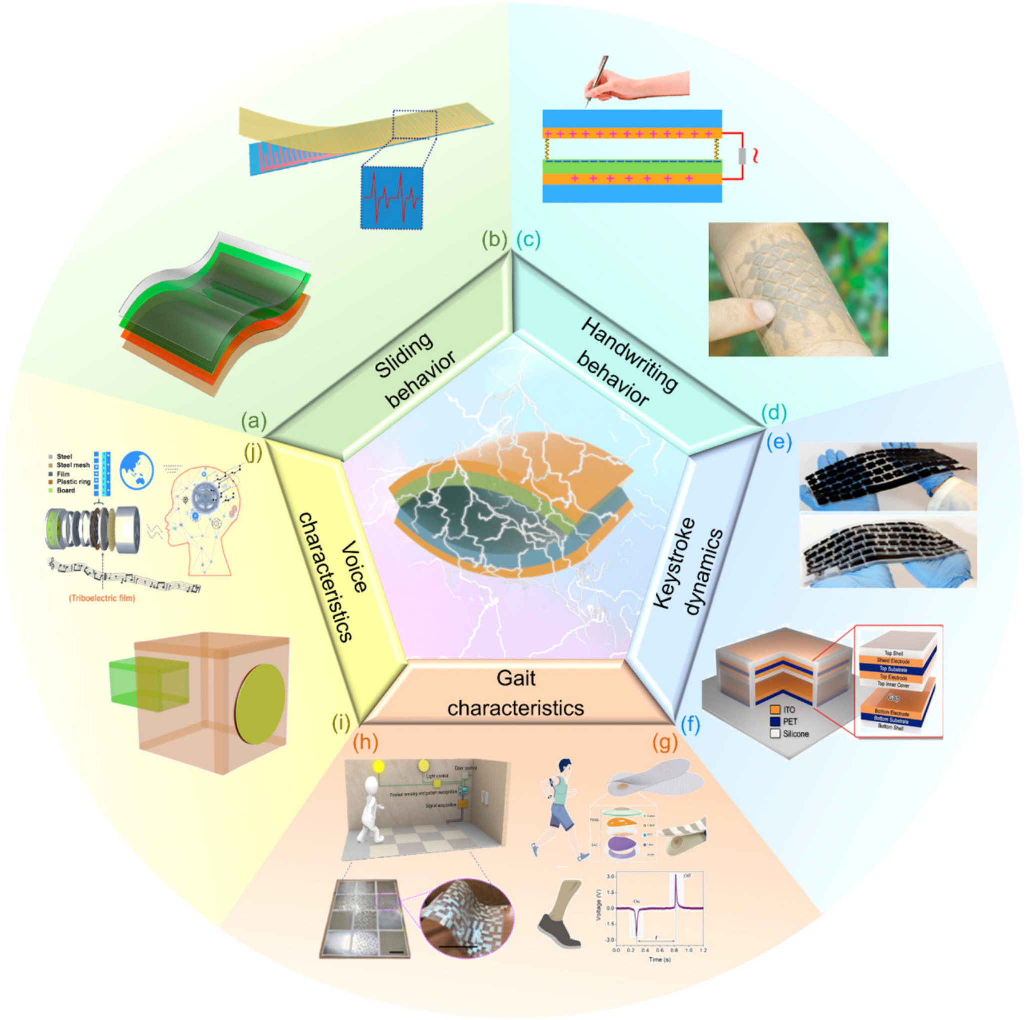

Fig. 1 TENGs as self-powered sensors for monitoring different kinds of biometric characteristics, including sliding behavior, handwriting behavior, keystroke dynamics, gait characteristics, and voice characteristics. (a) Reprinted with permission from ref. 31. Copyright 2016, American Chemical Society. (b) Reprinted with permission from ref. 32. Copyright 2018, Wiley-VCH. (c) Reprinted with permission from ref. 33. Copyright 2020, Elsevier B.V. (d) Reprinted with permission from ref. 34. Copyright 2021, The American Association for the Advancement of Science. (e) Reprinted with permission from ref. 35. Copyright 2016, American Chemical Society. (f) Reprinted with permission from ref. 36. Copyright 2018, Elsevier. (g) Reprinted with permission from ref. 37. Copyright 2019, Wiley-VCH. (h) Reprinted with permission from ref. 38. Copyright 2020, Nature Publishing Group. (i) Reprinted with permission from ref. 39. Copyright 2014, American Chemical Society. (j) Reprinted with permission from ref. 40. Copyright 2022, Elsevier B.V.

city-induced medium polarization, which is the theoretical basis for the existence of electromagnetic waves. The second term $\frac{\partial \mathbf{P}_s}{\partial t}$ is the current generated due to the polarization of electrostatic charges in medium boundary, which is named the *Wang term*. This term is directly related to the output current of the nanogenerator, indicating that TENGs were an important application of the Maxwell displacement current in energy and sensor fields.

Since the first TENG was reported in 2012,[44] tremendous efforts have been made to harvest mechanical energy in the environment by different modes using TENGs. According to the circuit connection methods and applied loading direction in the actual application environment for energy harvesting, four different working modes can be selected, including vertical contact-separation (CS) mode, lateral sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FT) mode (Fig. 2).[45] The vertical CS model relies on the polarization of two triboelectric layers in vertical movement. In general, the CS mode is particularly suitable for harvesting the energy generated in intermittent impact or shock, cyclic motions.[46–48] Due to the advantages of simple preparation, high instantaneous output power, and easy multilayer integration, the vertical CS mode has been widely applied to self-powered sensor systems.[49–53] The LS mode depends on lateral polarization, which is caused by tangential motion friction between two contact surfaces. Compared to the vertical CS mode, the triboelectric charges generated by LS mode sliding are much more effective than the pure contact, which helps to

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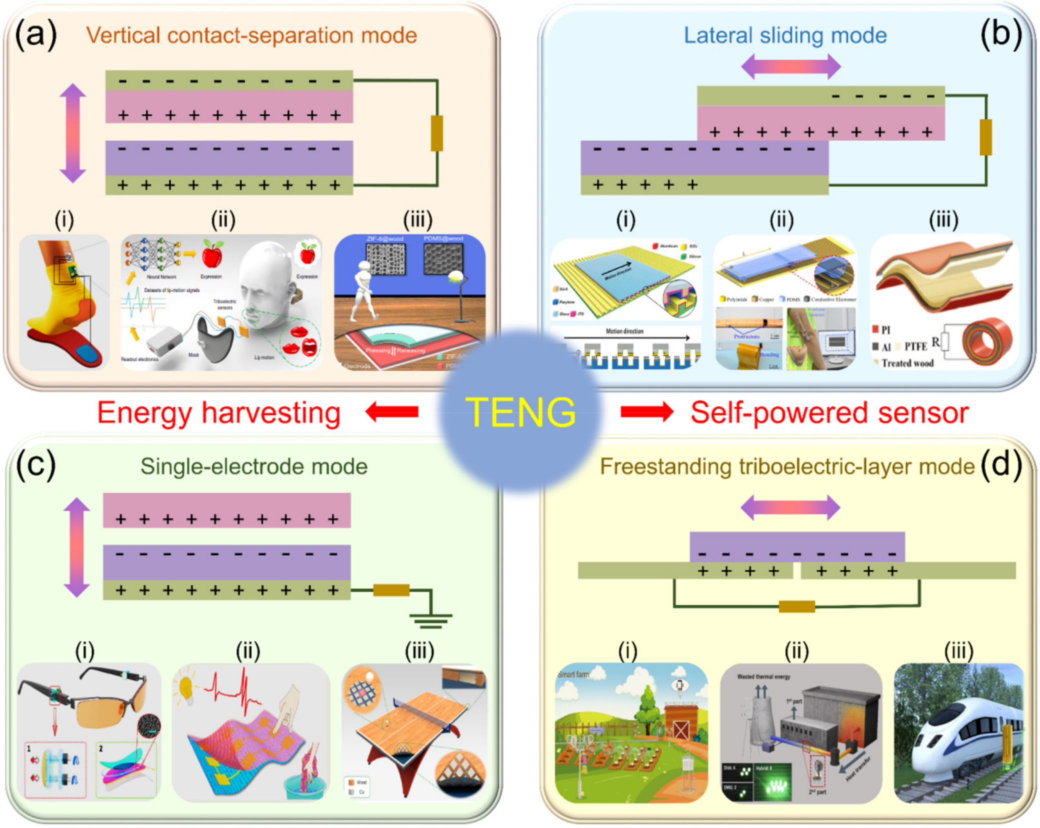

Fig. 2 Four fundamental operational modes of TENGs, including the (a) vertical contact-separation mode, (b) lateral sliding mode, (c) single-electrode mode, and (d) freestanding triboelectric-layer mode. (a) (i) Reprinted with permission from ref. 49. Copyright 2017, Elsevier B.V. (a) (ii) Reprinted with permission from ref. 50. Copyright 2022, Nature Publishing Group. (a) (iii) Reprinted with permission from ref. 51. Copyright 2021, Elsevier. (b) (i) Reprinted with permission from ref. 69. Copyright 2013, Wiley-VCH. (b) (ii) Reprinted with permission from ref. 58. Copyright 2017, Elsevier B.V. (b) (iii) Reprinted with permission from ref. 70. Copyright 2022, Wiley-VCH. (c) (i) Reprinted with permission from ref. 71. Copyright 2017, The American Association for the Advancement of Science. (c) (ii) Reprinted with permission from ref. 72. Copyright 2018, American Chemical Society. (c) (iii) Reprinted with permission from ref. 73. Copyright 2019, Nature Publishing Group. (d) (i) Reprinted with permission from ref. 66. Copyright 2021, Wiley-VCH. (d) (ii) Reprinted with permission from ref. 67. Copyright 2021, Elsevier B.V. (d) (iii) Reprinted with permission from ref. 68. Copyright 2021, American Chemical Society.

enhance power output. The LS mode is excellent at harvesting energy from rotational, air/water flow.[54–56] And it has also been successfully applied as a velocity sensor,[57] and tactile sensor.[58,59] The SE mode has a simple structure with only one electrode, which can be used to harvest energy from freely moving objects. Based on this advantage, such a working mode is widely used in many sensing scenarios, like body motion sensors,[60,61] self-powered trajectory, velocity sensors,[62,63] *etc*. The FT model TENG is composed of two electrodes and a friction layer, which is mainly used for rotational energy collection.[64,65] Self-powered sensing based on the FT mode has been widely applied to intelligent agricultural/industrial/traffic sensing systems.[66–68] These four modes have different mechanical triggering conditions due to different structures. According to the requirements of the actual scene application, one or more suitable hybrid modes can be selected. For the triboelectric self-powered intelligent sensors used in biometric authentication, the CS mode is usually applied in monitoring handwriting behavior, keystroke dynamics, gait characteristics, and voice characteristics. Besides, the LS mode and FT mode are more suitable for the study of sliding behavior. The SE mode is the most widely used and can be applied in these five biometric authentication systems.

3. Self-powered sensing for biometric authentication

3.1 Sliding behavior

As highly flexible and sensitive body parts, our hands can do various movements, including sliding, typing, grabbing, *etc*. and each person's sliding behavior has its unique personal characteristics (including finger size, pressing force, sliding speed, pause time, and corresponding sequences), which can be used for biometric recognition. By converting simple sliding motions into electrical signals, TENGs can be used as potential sensors for sliding behavior detection in a self-

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powered way. After signal extraction and analysis, the obtained output signals are capable of accurately reflecting individual characteristics, which can also be used for biometric recognition.

For sliding behavior, considering the range and flexibility of the finger movement in actual application, the structure of the sensor is generally designed to be light, portable, and easy to operate with one hand. In 2016, Luo *et al.* designed a transparent and flexible sliding self-charging power film.[31] As shown in Fig. 3a, the first part is a TENG mainly composed of a fluorinated ethylene propylene (FEP) friction layer, grid-like indium tin oxide (ITO) electrodes, and a polyethylene terephthalate (PET) substrate, and the second part is an all-solid-state transparent and flexible supercapacitor array containing three-dimensional Au@MnO$_2$ nanocomposite electrodes. During sliding motions, individual characteristics from generated electric signals can be accurately identified, and an intelligent unlock system was designed to show its application potential in the security system of touchpad technology. Later, Yuan *et al.* developed a transparent and flexible triboelectric sensing array (Fig. 3b).[74] The self-powered sensing array consists of an electrification FEP layer, an elastic polydimethylsiloxane (PDMS) interlayer, and a PET substrate with grid ITO electrodes on it. The trajectory of sliding motion can be well tracked by the fabricated device. Based on this, it can be used to unlock the user interface intelligently. Furthermore, Yuan *et al.* designed a triboelectric-based transparent secret code that enables self-powered sensing and information identification simultaneously, as shown in Fig. 3c.[32] The secret code has three flexible transparent layers, FEP, PET, and ITO. For the sliding or roll-to-roll motion, the length and interval of the designed ITO stripes have an obvious influence on the output signals. Then, a smart access control system was designed to realize the control of door access, showing great application potential of the transparent secret code in personal identity identification, security protection, and commodity circulation.

For a better human-machine interface, Chen *et al.* presented a flexible and self-powered finger trajectory sensing patch based on the TENG, in which a two-dimensional (2D) sensor and a one-dimensional (1D) sensor are used for movement control of in-plane and out-of-plane separately (Fig. 3d).[75] The contact location can be perceived by detecting the generated current and voltage on the four electrodes from the sliding motion on the surface of the 2D sensor. The con-

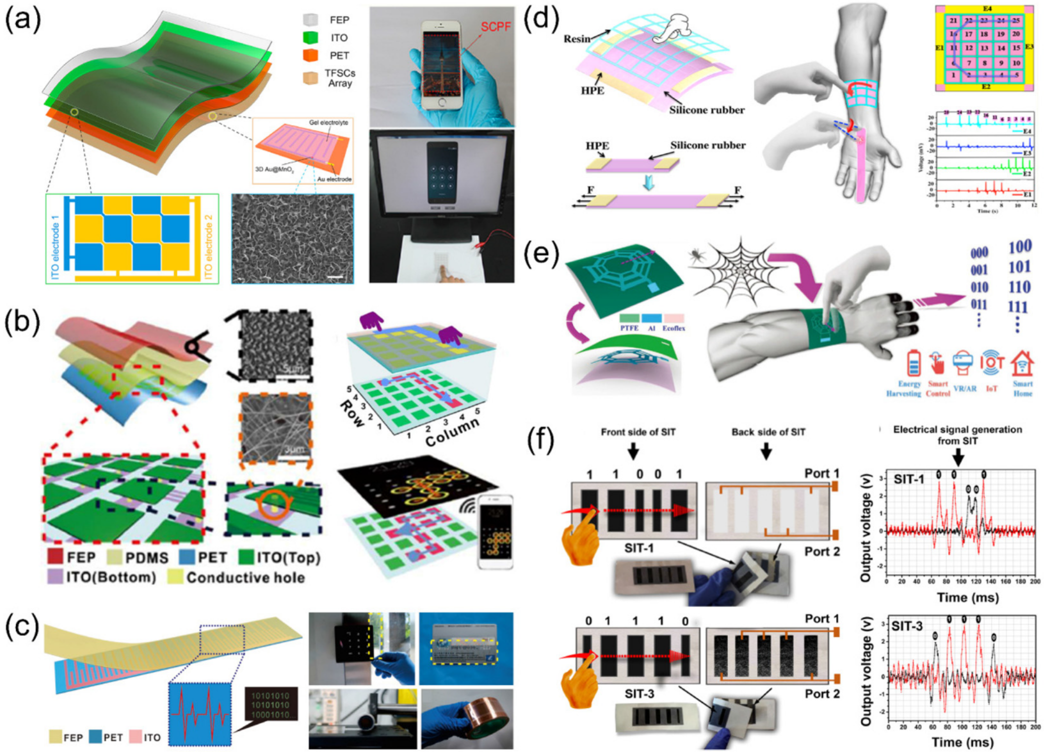

Fig. 3 TENG-based self-powered intelligent sensors for monitoring sliding behavior. (a) Transparent and flexible self-charging power film and its application in a sliding unlock system in touchpad technology. Reprinted with permission from ref. 31. Copyright 2016, American Chemical Society. (b) Transparent and flexible triboelectric sensing array for touch security applications. Reprinted with permission from ref. 74. Copyright 2017, American Chemical Society. (c) Triboelectric based transparent secret code for self-powered sensing and information identification. Reprinted with permission from ref. 32. Copyright 2018, Wiley-VCH. (d) Triboelectric self-powered wearable flexible finger trajectory sensing patch as a 3D motion control interface. Reprinted with permission from ref. 75. Copyright 2018, American Chemical Society. (e) Bio-inspired spider-net-coding interface and its diversified applications. Reprinted with permission from ref. 76. Copyright 2019, Wiley-VCH. (f) Ultrathin triboelectric touch-interactive power paper and corresponding electrical signals under the finger swiping. Reprinted with permission from ref. 77. Copyright 2022, Elsevier B.V.

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tinuous state of movement of a finger on the surface of the sensing patch such as trajectory, velocity, and acceleration, can also be recorded. Through further combination with the 1D triboelectric sensor, three-dimensional (3D) spatial information can be obtained and applied to real-time control of robot manipulators, which shows great potential in robotics, virtual reality (VR), augmented reality (AR), medical care, and other fields. To simplify the structure and reduce the number of electrodes, Shi *et al.* designed a bio-inspired spider-net-coding interface for multidirectional control by uniting information coding electrodes into a single one, as shown in Fig. 3e.[76] The device only comprises flexible thin polymer films (Ecoflex substrate and polytetrafluoroethylene (PTFE) friction layer) and patterned Al electrodes. Two types of information codings, L/S coding related to large/small electrode width and 0/1 coding meaning with/without the electrode at a predefined position, are designed. When the finger slides on the device, the voltage signal related to the coding information will be generated. The interface can realize the multiple direction control and detect different output signal patterns, showing excellent application value in multi-directional control, security systems, and wearable electronics. In addition, from the view of smartness and sustainability, Ferreira *et al.* developed an ultra-thin (~0.18 mm) self-powered paper-based prototype as a touch-interactive electronic tag, in which graphite pencils can also be utilized as the electrode material (Fig. 3f).[77] When swiping with a finger, electrical signals would be generated and programmed into digital signals. With this functionalized paper, a self-powered security identification system was further designed.

3.2 Handwriting behavior

As a more complex motion and an important individual behavioral characteristic, handwriting-based signature has been widely used to authenticate identity.[78–80] Since a TENG is a kind of sensitive sensor for detecting external mechanical signals, after coupling with advanced information processing capabilities such as machine learning, it can provide an effective approach to recognizing handwriting behavior.

As shown in Fig. 4a, Zhang *et al.* developed a kind of leaf-inspired TENG with a micro-nano structure texture, which can be used as a smart self-powered pad for handwriting recognition.[33] To fabricate a textured TENG, a copper (Cu) film was attached to the polymethyl methacrylate (PMMA) substrate as the top part, and both sides of another Cu film were respectively attached to the bioinspired PDMS and PMMA substrates as the bottom part. The two parts were then connected together by springs with a spacing between them. It can be found that the TENG can acquire handwriting signals of different testers and their unique features can be successfully identified by the machine learning method, demonstrating its great application potential in handwriting signature recognition, private information protection, and security defense. Ji *et al.* designed a highly sensitive and flexible self-powered intelligent writing pad based on a TENG and the automatic machine learning data analysis algorithm for handwriting signal detection (Fig. 4b).[81] Cu mesh and NaCl molded PDMS are utilized as triboelectric layers. The arc shaped wavy structure of the copper mesh creates conditions for contact and separation actions. To realize handwriting recognization, they established a letter fingerprint library, which contains 26 letters' handwriting signals with 520 samples. To study the inherent relationship of each letter hierarchical clustering and similarity matrix were chosen. After extracting and analyzing the letter features, a model was developed for the fingerprint identification of 26 letters and achieved a high recognition accuracy of 93.5%.

By utilizing the triboelectrification and piezoelectric effect synchronically, Guo *et al.* developed an active multifunctional electronic skin that can independently detect velocity, acceleration, pressure, and contact trajectory.[82] Taking its sensitivity and precision advantage, a smart signature system was designed to identify personal signature habits and achieve anti-counterfeiting, showing its good potential as a promising human-machine interaction candidate. Subsequently, based on the horizontal-vertical symmetrical electrode array structured TENG, they designed a type of intelligent human-machine interaction interface and combined it with supervised machine learning methods to record and recognize handwriting behavior.[34] Fig. 4c shows the device and its schematic recognition process. After being fabricated, two patterned PDMS-AgNWs were stacked vertically, and then connected and encapsulated by liquid PDMS. By introducing the neural network of the K-nearest-neighbor classifier algorithm, different handwritten characters can be well recognized. More than that, it can realize the anticounterfeiting recognition of writing habits. The TENG-based intelligent human-machine interface shows a broad prospect in signature security and label recognition applications.

For handwriting behavior, considering the convenience of users in practical applications, the structure of the sensing device is generally designed as a writing board. Based on a transparent and flexible electrode-miniaturized TENG array, Ba *et al.* designed a physical and electronic double writing board, as shown in Fig. 4d.[83] Each TENG unit represents one pixel, in which the PET substrates, the ITO top electrodes, the silicone gasket/friction layer are assembled together. When writing, the nib trajectory was reflected by the electrical signals from the self-powered sensor array and synchronized with the computer for human-machine interaction. By introducing a biodegradable carboxymethyl chitosan-silk fibroin film, Shen *et al.* reported a wearable TENG and used it in a human-machine interface for calligraphy practice and correction (Fig. 4e).[84] In the application demonstration, the human-machine interface can recognize and correct three representative letters automatically. Moreover, to verify a VR writing control, a training program was designed, showing the prospect of a human-machine interface in establishing an intelligent lifestyle.

3.3 Keystroke dynamics

Apart from the abovementioned behavior, typing is another kind of common behavior during human-machine interaction in modern society. In 1975, based on people's typing character-

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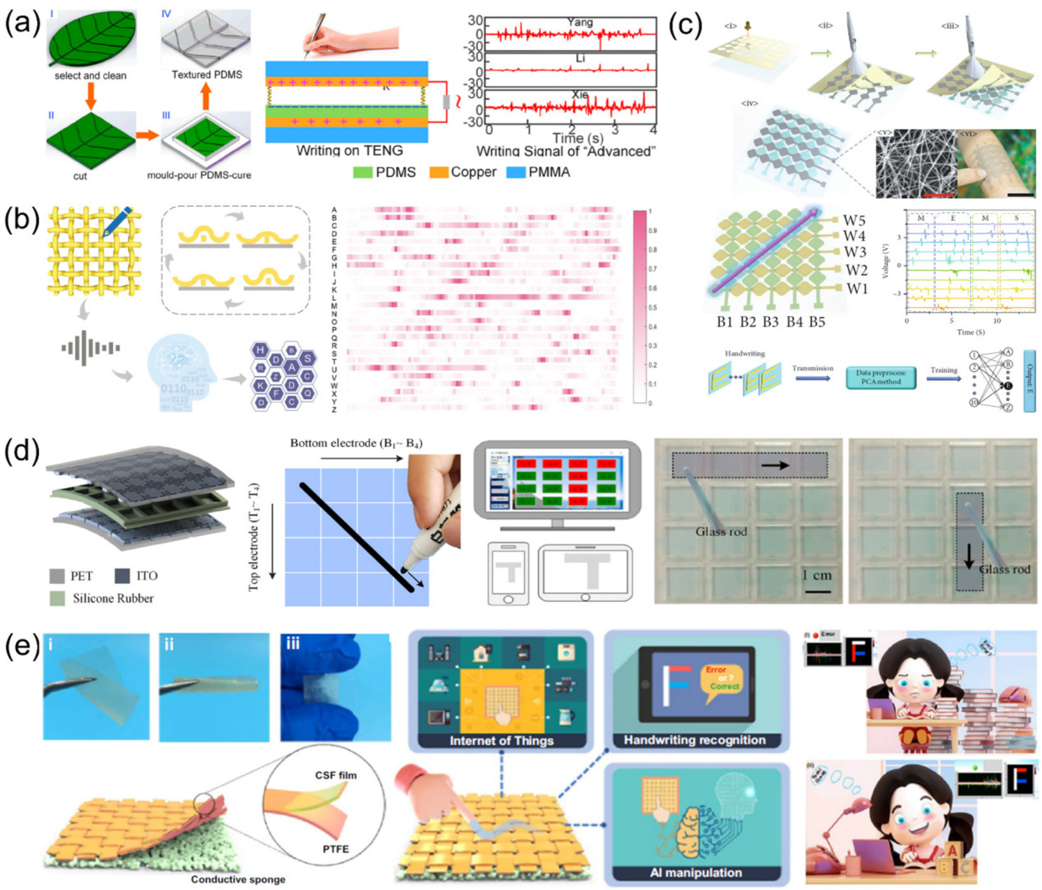

Fig. 4 TENG-based self-powered intelligent sensors for monitoring handwriting behavior. (a) Leaf-inspired TENG is used as a smart self-powered pad for handwriting recognition. Reprinted with permission from ref. 33. Copyright 2020, Elsevier B.V. (b) Copper mesh based TENG as a self-powered writing pad *via* automatic machine learning data analysis algorithm for handwriting signal detection. Reprinted with permission from ref. 81. Copyright 2020, Wiley-VCH. (c) TENG-based self-powered intelligent human-machine interaction interface combined with supervised machine learning methods for handwriting behavior recording and recognition. Reprinted with permission from ref. 34. Copyright 2021, The American Association for the Advancement of Science. (d) Physical and electronic double writing board based on an electrode-miniaturized TENG array for self-powered trajectory-tracking microsystems. Reprinted with permission from ref. 83. Copyright 2021, Elsevier B.V. (e) Biodegradable triboelectric film-based wearable electronics used in human-machine interface for calligraphy practice and correction. Reprinted with permission from ref. 84. Copyright 2022, Springer Nature.

istics, Spillane proposed the concept of keystroke dynamics.[85] In later years, it was verified that the unique characteristics of typing patterns can be identified.[86] As a mechanical-to-electrical conversion device, TENG in a contact-separation mode or a single-electrode mode can be easily used with a keyboard for energy harvesting and behavioral characteristics recognition from the user's typing.[87,88]

In 2014, Chen *et al.* first reported a self-powered, non-mechanical-punching intelligent keyboard (Fig. 5a).[89] Its key functional element is composed of two ITO electrode layers with a PET layer in the middle, and an electrification FEP layer with nanowire arrays by reactive ion etching on the ITO surface. The intelligent keyboard assembled from the functional elements and a commercial keyboard can trace and record typed content by detecting the dynamic time intervals and the force during typing. By identifying the personal characters of typing using keystroke dynamics, it is very suitable to establish a biometric authentication system. Based on this work, Zhao *et al.* further developed a deep-learning-based keystroke dynamics identification method used on the intelligent keyboard for increased security.[90] One significant advantage is that it can process the raw signals directly, which is conducive to simplifying the verification and identification system. The effectiveness is well demonstrated in experiments on 104 typing datasets. The proposed method can automatically recognize the typing pattern, showing its application potential in access control, cyber security, and personal information management. Li *et al.* also reported a highly flexible TENG covering on the keyboard to harvest typing mechanical energy (Fig. 5b).[35] The TENG was made of solely elastomeric silicone materials, including two supporting layers, two electrode layers, and a dielectric layer. In particular, when comparing the "patterns" of different operators, it is significant to observe the differences due to distinct typing habits.

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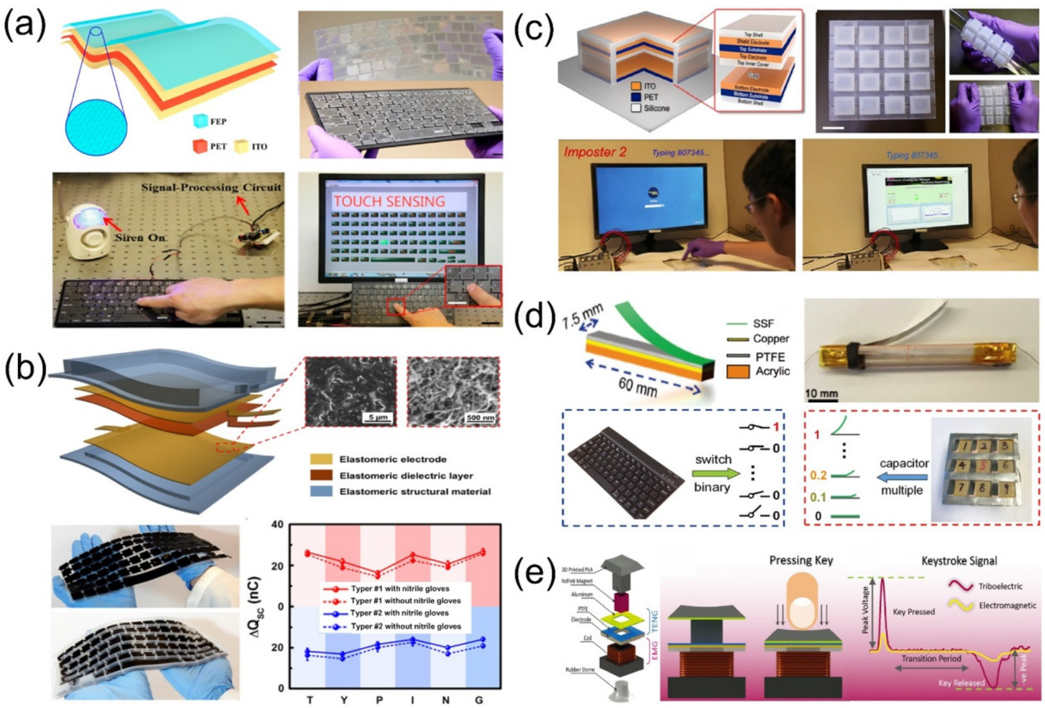

Fig. 5 TENG-based self-powered intelligent sensors for monitoring keystroke dynamics. (a) TENG-based self-powered intelligent keyboard for the biometric authentication system. Reprinted with permission from ref. 89. Copyright 2014, American Chemical Society. (b) All-elastomer-based TENG as a keyboard cover to harvest typing energy and distinct typing habits. Reprinted with permission from ref. 35. Copyright 2016, American Chemical Society. (c) Elastic-beam TENG-based smart keyboard for keystroke dynamics-based biometric authentication. Reprinted with permission from ref. 36. Copyright 2018, Elsevier. (d) TENG array for keystroke dynamics enabled authentication and identification. Reprinted with permission from ref. 91. Copyright 2018, Wiley-VCH. (e) Self-powered hybrid electromagnetic-triboelectric nanogenerators/sensors integrated with neural network-based artificial intelligence for a keystroke dynamics-driven biometric authentication system. Reprinted with permission from ref. 92. Copyright 2021, Wiley-VCH.

Different from combining a TENG-based cover with a traditional keyboard, Wu *et al.* developed a kind of triboelectric keystroke to fabricate a keystroke dynamics-based security system (Fig. 5c), with an authentication and identification accuracy of up to 98.7%.[36] The main structure of the self-powered, stretchable, and water/dust proof triboelectric keystroke device is made of silicone and three electrodes including a shield electrode. More importantly, the embedded shield electrode could avoid inadvertent touch effectively and improve the signal-to-noise ratio obviously. By integrating a numeric keypad consisting of 16 triboelectric keys and the support vector machine algorithm-based software platform, the identification system can identify different users even if they typed the same codes. The system provides a higher level of cyber security, showing its promising and meaningful application in the computing and financial industry. Besides, Chen *et al.* developed a kind of elastic-beam TENG with stainless steel foil in an arc structure, which can also be used in a smart keyboard for keystroke dynamics-based biometric authentication, as illustrated in Fig. 5d.[91] Different from traditional structures, its working performance mainly depends on the contact area and separating distance, bringing advantages of elasticity, high sensitivity, and ultrahigh frequency response. Furthermore, Maharjan *et al.* reported a new self-powered hybrid electromagnetic-triboelectric nanogenerators/sensors integrated with neural network-based artificial intelligence for a biometric authentication system with keystroke dynamics-driven, as shown in Fig. 5e.[92] The electromagnetic generator is composed of a rectangular neodymium (Nd) magnet inside a keycap leg and a rectangular Cu coil set around the holder. The TENG in a single electrode contact-separation mode consists of a positive triboelectric aluminum (Al) film and a negative triboelectric PTFE film with a Cu electrode on the backside. With the same key dimensions, the hybrid sensor shows a high accuracy of 99% and double security than individual sensor-based authentication. In the above studies, in order to efficiently perceive the mechanical trigger conditions of the keystrokes, the design of the sensor must ensure that the size of the triboelectric sensing unit is similar to the keyboard keys.

3.4 Gait characteristics

Gait recognition is a biometric recognition technology that has received increasing attention. During human walking, every gait refers to a state of motion, which can reflect a variety of information.[93–96] TENGs can convert the mechanical energy in this process into electrical signals effectively, which makes

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them a promising sensor to monitor gait characteristics and realize subsequent recognition.

In practical application scenarios, the structure and size of the sensing devices used for monitoring gait characteristics mainly depend on the integrated object. A common method is simply combining the TENG-based sensors with various footwear. As shown in Fig. 6a, Lin *et al.* developed a wearable smart insole used for real-time multifunctional gait monitoring.[37] Two TENG-based sensors were placed in the front and rear of the smart insole. Each sensor consists of an elastic air chamber part and a convex TENG part on top of it. As the forefoot steps on the floor, the front sensor first outputs a negative peak, followed by a positive peak meaning off. Then the rear sensor repeats this process. By analyzing the abovementioned traits of signals, different gait patterns can be recognized accurately, like stepping, walking, and running, which make the smart insole suitable for further application in gait rehabilitation treatment and fall-down event detection. Later, Xiong *et al.* designed a self-healable gas-solid interacting TENG and inserted it into a shoe for energy harvesting, exhibiting the potential for gait monitoring.[97] As an important kind of footwear, socks were chosen and utilized as well. Fig. 6b shows the deep learning-enabled triboelectric smart socks developed by Zhang *et al.*, by which the user's activity can be monitored and identified after gait analysis.[98] The textile-based TENG sensor consists of a nitrile thin film, a frustum patterned silicone rubber film, and two conductive textiles attached to them. With the help of an optimized deep learning model, a 93.54% identification accuracy of 13 users was realized, and a 96.67% detection accuracy of 5 different human activities was achieved as well. By integrating a poly(3,4-ethylenedioxythiophene) polystyrenesulfonate-coated fabric TENG and lead zirconate titanate piezoelectric chips, Zhu *et al.* also developed a self-powered and self-functional cotton sock, which can achieve foot-based energy harvesting and sensing different physiological signals including gait information for walking pattern recognition and motion tracking.[99]

Other kinds of devices such as a soft and stretchable self-powered band reported by Han *et al.* can be looped around body parts like legs and arms to gain a gait pattern (Fig. 6c).[100] The self-powered band is simply composed of a rubber tube with physiological saline filled in it. By detecting muscle

Fig. 6 TENG-based self-powered intelligent sensors for monitoring gait characteristics. (a) TENG-based wearable smart insole for real-time multifunctional gait monitoring. Reprinted with permission from ref. 37. Copyright 2019, Wiley-VCH. (b) Deep learning-enabled triboelectric smart socks for gait analysis. Reprinted with permission from ref. 98. Copyright 2020, Springer Nature. (c) Soft and stretchable triboelectric band for self-powered gait pattern-based identity recognition. Reprinted with permission from ref. 100. Copyright 2018, Elsevier B.V. (d) Deep learning enabled smart mats as a scalable floor monitoring system. Reprinted with permission from ref. 38. Copyright 2020, Nature Publishing Group. (e) Self-powered smart floor system with path analysis and safety monitoring functions. Reprinted with permission from ref. 101. Copyright 2022, American Chemical Society. (f) TENG-based self-powered electronic textiles for an intelligent footwear system and identity recognition carpet. Reprinted with permission from ref. 102. Copyright 2020, Nature Publishing Group.

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activity, the band can provide feedback on various information quantitatively, such as the walking step, speed, and distance, which can be further used for identity recognition.

On the other side of interactive interfaces during walking, the motion-sensing floor or the applied covering on it is also a good choice for gait recognition. When people walk on the floor with TENG sensors embedded in them, the output electric signals can also show gait characteristics. As illustrated in Fig. 6d, Shi *et al.* developed a smart floor monitoring system, which integrates scalable self-powered friction electric floor mats and deep learning-based data analysis.[38] According to the high accuracy real-time sensing results, the system can realize indoor positioning, and activity monitoring including 96.00% high accuracy gait prediction, and individual recognition. By utilizing an effective and simple strategy to treat natural wood, a self-powered wood-based triboelectric sensor possessing superior sensitivity, flexibility, stability, and thinness was reported by Shi *et al.*[101] Integrated with the wooden floor, an intelligent floor monitoring system was constructed to realize gait recognition and health monitoring (Fig. 6e). Furthermore, designed by Dong *et al.*, Fig. 6f shows two human-machine interaction products for human motion monitoring and identity recognition, a smart shoe and a self-powered smart carpet.[102] Both of them are based on the electronic textile with a 3D five-directional braided structured TENG, which exhibits the advantages of high flexibility, structural integrity, cyclic washability, shape adaptability, and superior mechanical stability.

3.5 Voice characteristics

Talking with each other is a vital communication approach for human beings to acquire information. During this process, unique voice characteristics are distinguished and recognized by our auditory system. More importantly, voice sensing and recognition is widely applied in our daily life, such as speech input and security monitoring.[103–105] Different from traditional acoustic sensors, TENG can convert sound waves into electrical signals in a self-powered way and has been tried for many applications.

Yang *et al.* reported the first TENG-based acoustic sensor for sound recording in 2014 (Fig. 7a).[39] The TENG is composed of a holey Al film electrode and a PTFE thin film with deposited Cu as another electrode under carefully designed straining conditions. The self-powered sensor can automatically detect the location of an acoustic source with an error of less than 7 cm. Besides, an array of devices was used to obtain a high bandwidth of resonance frequencies from 10 to 1.7 kHz. Subsequently, Fan *et al.* designed a paper-based TENG for acoustic energy harvesting and self-powered sound recording with the advantages of board bandwidth, light weight, ultra thinness, and rollability, as shown in Fig. 7b.[106] The TENG is made of membranes with reasonable holes on one side for an enhanced broadband acoustic response. With a thickness of 125 μm, it is suitable to be implemented onto a cell phone. Moreover, it can also be used as a self-powered microphone with no angular dependence for all-sound recording. Following their first work on TENG-based acoustic sensors, Yang *et al.* further developed an eardrum-inspired triboelectric membrane acoustic sensor for self-powered voice recognition (Fig. 7c).[107] The fabricated acoustic sensor has a superior sensitivity (51 mV Pa^{-1}) with a fast response time (<6 ms) as well as a low pressure detection limit (2.5 Pa) and achieves a wide working bandwidth from 0.1 to 3.2 kHz. The self-powered device can distinguish and recover human throat voice with an extremely noisy or windy background, further affirming its value in high-accuracy single-sensor multimodal biometric authentication.

In voice recognition and authentication, the triboelectric sensing devices are generally designed to be portable and wearable for ease of use. In order to supply an external hearing aid for an intelligent robot, Guo *et al.* proposed a self-powered frequency-response tunable triboelectric auditory sensor, which is ultrahigh sensitive (110 mV dB^{-1}) and broad frequency responsive (100 to 5 kHz) (Fig. 7d).[108] By incorporating into intelligent robotic devices, the triboelectric auditory sensor demonstrated high-quality music recording performance and accurate voice recognition ability, indicating its excellent intelligent human-robot interaction. Due to the controllable resonant frequency, a specific sound wave can be amplified naturally. Besides, a low-power consumption hearing aid with simple signal processing was proposed, further showing the advantages of TENG technology in the new generation of auditory systems. Also based on TENG, Arora *et al.* reported a self-powered audio triboelectric ultra-thin rollable nanogenerator microphone for sound recording and analysis, which has favorable audio performance.[109] More importantly, it can be prepared in a simple way and deployed easily, indicating its application potential in a self-sustainable interactive system. Inspired by the morphology and function of the human auditory perception system, TENG-based acoustic sensors were extended and applied to urban sound management by Yao *et al.*[110] With the deep learning technique, an intelligent sound monitoring and identification system was successfully constructed, which can recognize familiar road sound types with high accuracy (99%) and precision.

Although some advances have been made in flexible microphones, further research is still needed in human-robot interfaces that integrate multiple functions and more sophisticated artificial intelligence. Recently, a novel self-powered triboelectric acoustic sensor based on the unique capacitance model of triboelectric technology was fabricated by Yang *et al.*[40] As shown in Fig. 7e, the acoustic sensor is mainly composed of ten parts. It can cover the full frequency range of human hearing (20 to 20 kHz) and possess higher frequency resolution and higher sensitivity. Thus, the triboelectric acoustic sensor can be applied in many scenarios, such as voice content inputting, human-robot interaction, *etc.* To further realize robotic intelligence, Sun *et al.* reported graphene-based dual-function acoustic transducers used as an artificial ear and an artificial mouth separately for machine learning-assisted human-robot interfaces (Fig. 7f).[111] Artificial ear is implemented by the triboelectric acoustic sensing mechanism where the artificial mouth uses the thermoacoustic sound

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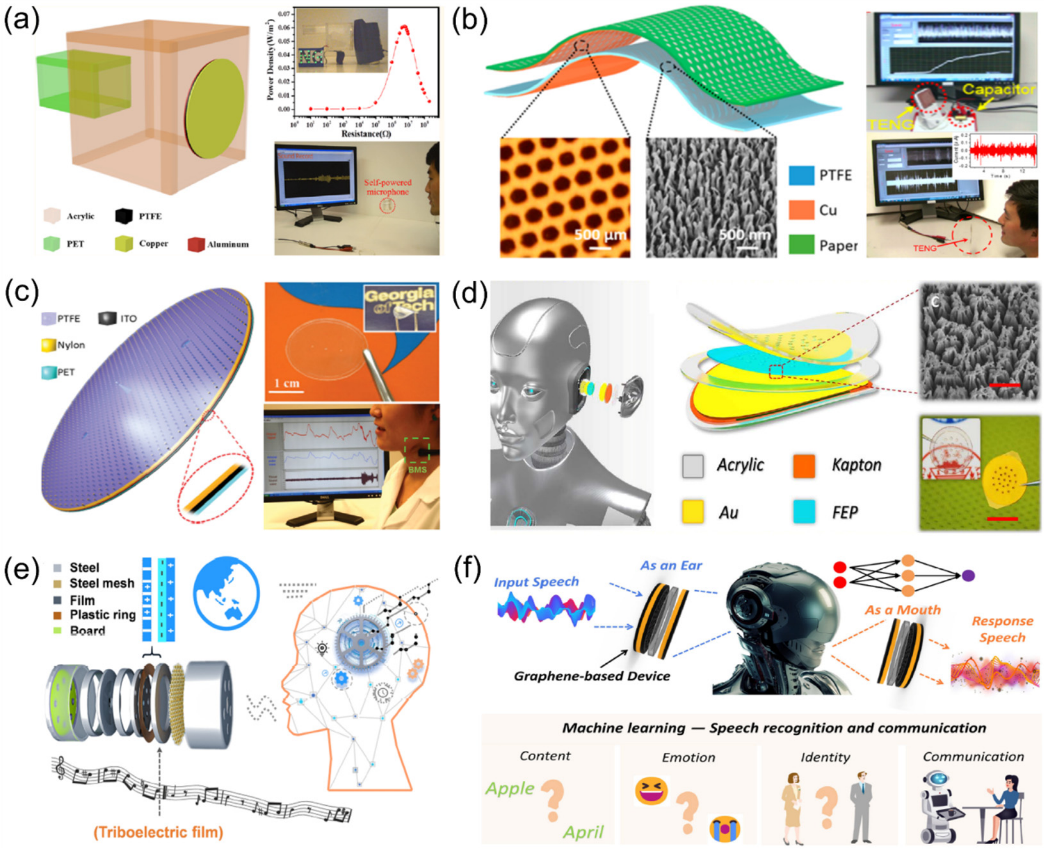

Fig. 7 TENG-based self-powered intelligent sensors for monitoring voice characteristics. (a) Triboelectrification-based organic film nanogenerator for acoustic energy harvesting and self-powered active acoustic sensing. Reprinted with permission from ref. 39. Copyright 2014, American Chemical Society. (b) Ultrathin, rollable, paper-based TENG for cell phone sound wave energy harvesting and self-powered sound recording. Reprinted with permission from ref. 106. Copyright 2015, American Chemical Society. (c) Eardrum-inspired active sensors for self-powered throat-attached anti-interference voice recognition. Reprinted with permission from ref. 107. Copyright 2015, Wiley-VCH. (d) A highly sensitive, self-powered triboelectric auditory sensor for social robotics and hearing aids. Reprinted with permission from ref. 108. Copyright 2018, The American Association for the Advancement of Science. (e) High-sensitivity and ultra-wide spectrum multifunctional triboelectric acoustic sensor for broad scenario applications. Reprinted with permission from ref. 40. Copyright 2022, Elsevier B.V. (f) Graphene-based dual-function acoustic transducers for machine learning-assisted human-robot interfaces. Reprinted with permission from ref. 111. Copyright 2022, Wiley-VCH.

emission mechanism. And both of them used the key multi-functional laser-induced graphene for different purposes. The artificial ear in a TENG-based microphone form has a wide spectrum of 20-20 kHz with ultrahigh sensitivity, high resolution, good stability, and long operational durability. With machine learning, the multidimensional speech recognition and intelligent communication human-robot interface achieved a high accuracy of 99.66% and 96.63% from training and test datasets. Moreover, the introduction of the thermo-acoustic loudspeaker makes it possible to achieve barrier-free chat, creating a good foreground for robotic intelligence.

4. Application

4.1 Self-powered authentication for individual electronics

As shown in the previous section, we can see that the TENG can be utilized as a self-powered sensor for recognizing five kinds of biometric characteristics. Considering that the authentication process for individual electronics (such as personal computers, tablets, or mobile phones) involves mechanical movements, TENGs can be used as an additional part of individual electronics to further improve the safety level. Therefore, it will be a promising solution to provide superior security on current authentication systems without large modifications.

Guo *et al.* designed an electronic auditory platform for social robotics based on triboelectric auditory sensors (TAS).[108] This triboelectric sensor has ultra-high sensitivity and broadband response range (100 to 5000 Hz), and can promote efficient and accurate interaction between humans and robots. Fig. 8a shows a circular-type TAS, that could be installed onto a robot's ear part for high-accuracy music recording and voice recognition. The collected power spectral, voltage signal, and voice spectrogram from each person are distinctly different. After analyzing and comparing these signals, a self-powered sound recognition system was successfully built for dis-

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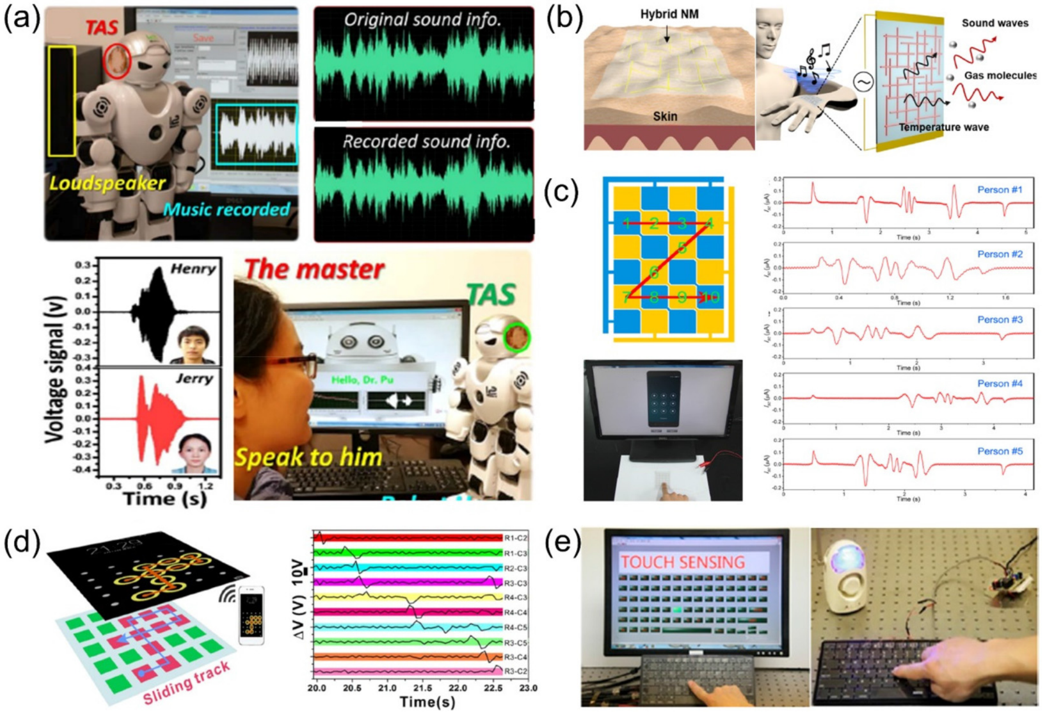

Fig. 8 Applications of TENGs for self-powered authentication for individual electronics. (a) The highly sensitive, self-powered triboelectric auditory sensor-based voice recognition system. Reprinted with permission from ref. 108. Copyright 2018, The American Association for the Advancement of Science. (b) Transparent and conductive nanomembranes with orthogonal silver nanowire arrays for skin-attachable loudspeakers. Reprinted with permission from ref. 112. Copyright 2018, The American Association for the Advancement of Science. (c) Transparent and flexible self-charging power film for an intelligent sliding unlock system. Reprinted with permission from ref. 31. Copyright 2016, American Chemical Society. (d) Schematic process of the intelligent sliding unlock, and the chronological track captured by the tactile sensing system. Reprinted with permission from ref. 74. Copyright 2017, American Chemical Society. (e) Intelligent keyboard as a self-securing system. Reprinted with permission from ref. 89. Copyright 2014, American Chemical Society.

tinguishing user's identity. In addition, Kang *et al.* also reported a self-powered wearable nanomembrane microphone based on triboelectric signals, which can provide outstanding acoustic sensing capabilities (Fig. 8b).[112] This nanomembrane microphone is further utilized to realize personal voice-based authentication, which can effectively prevent unauthorized users from accessing the computer system by analyzing their voiceprint.

To enhance the security level of personal electronics, the TENG-based self-powered certification system can also be integrated as an additional layer of electronics. Luo *et al.* developed a self-powered intelligent sliding unlock system based on the transparent TENG, which can be installed on the surface of the cellphone for recognizing the sliding characteristics.[31] As shown in Fig. 8c, according to their different sliding modes, finger sizes, applied pressure force, and sliding speed, the obtained output current signals of different people can be distinguished by the number, intensity, and time interval of current peaks. As a result, only those who truly match the preset sliding characteristics can unlock smoothly. This design will add a layer of security and effective protection to the current sliding authentication system. Besides, high sensitivity and large-scale arrays of tactile sensors are vital for human-machine interaction, mobile networks, and smart wearable devices. Yuan *et al.* developed a flexible and transparent triboelectric sensing array (TSA) with outstanding durability and synchronicity, which can realize touch sensing, motion monitoring, and spatial mapping in real time.[74] As shown in Fig. 8d, an intelligent unlock system is constructed based on the TSA, which can be triggered by the motion of fingers to produce signals in a certain series for self-powered identity authentication.

In daily life, keyboards are often used to input passwords or personal identification numbers (PINs) in computing devices. Chen *et al.* first proposed an intelligent keyboard based on the TENG, which can convert the mechanical stimulation applied to the keyboard into local electrical signals without using the external power supply, as shown in Fig. 8e.[89] By studying the keystroke features using the deep-learning method, this TENG-based intelligent keyboard can be utilized to develop a keystroke dynamics authentication system, which can effectively simplify the design and improve the recognition accuracy.[90] Considering its excellent authentication ability, this kind of TENG-based intelligent keyboard can be used to recognize the personal typing character, making it practical for developing a high-security authentication system based on the triboelectrification enabled keystroke dynamics.

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4.2 Self-powered home security

Personal information identification technology has recently become an important part of smart home devices. To date, a variety of secure and reliable personal information security systems have been developed.[113–115] As a vital component of smart home systems, sensing devices are extensively distributed in the home environment, which is the basis for the realization of smart home control.[116–119] TENGs can operate as self-powered sensors without using external power sources, which provides an effective approach for improving home security.

In 2017, Chen *et al.* designed a self-powered 2D barcode recognition system based on the sliding mode TENG.[120] This recognition system mainly consists of a barcode component and a reader, as shown in Fig. 9a. It's worth noting that the reference barcode component can easily recognize the signal under the random speed slide. Based on this advantage, a self-powered access control system for recognizing particular information is successfully designed. Voltage signals for identification will be generated by simply swiping the card with human hands, demonstrating its application potential in improving the safety level of home life. Subsequently, Li *et al.* proposed a TENG-based active sliding sensor for home security monitoring, as shown in Fig. 9b.[121] With ultra-high sensitivity and accuracy, the sliding sensor can detect the position, direction, velocity, and displacement of the device movement by using a dual interdigitated electrode pair struc-

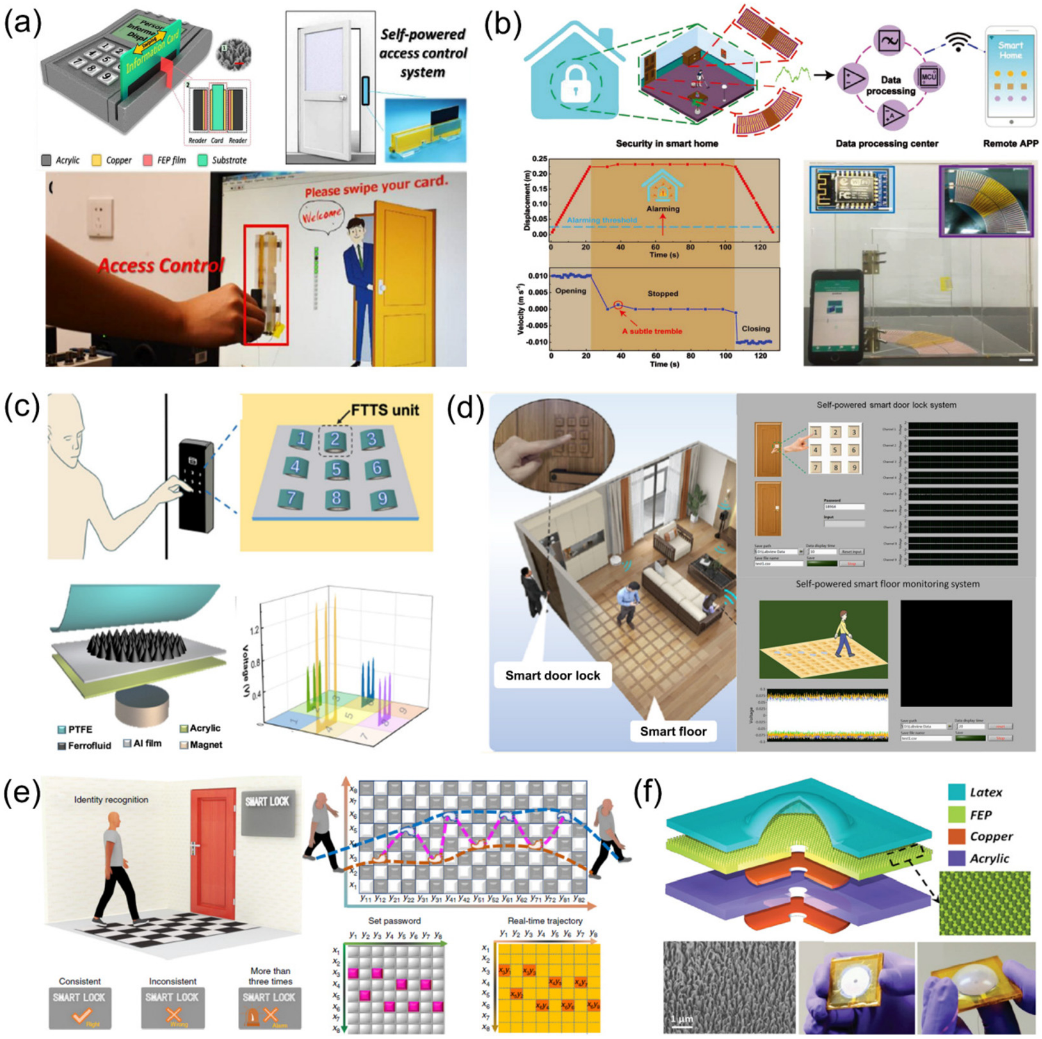

Fig. 9 Applications of TENGs for self-powered home security. (a) A self-powered 2D barcode recognition system based on sliding mode triboelectric nanogenerator for personal identification. Reprinted with permission from ref. 120. Copyright 2018, Elsevier B.V. (b) The interdigitated electrode-TENG-based motion sensor for the security monitoring system. Reprinted with permission from ref. 121. Copyright 2018, Wiley-VCH. (c) A novel password lock with variable force requirement. Reprinted with permission from ref. 122. Copyright 2022, Springer Nature. (d) The smart door lock system based on WTSSs. Reprinted with permission from ref. 101. Copyright 2022, American Chemical Society. (e) The self-powered identity recognition system, and the human walking trajectories on the identity recognition carpet. Reprinted with permission from ref. 102. Copyright 2020, Nature Publishing Group. (f) The membrane-based self-powered triboelectric sensors. Reprinted with permission from ref. 123. Copyright 2014, Wiley-VCH.

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ture. A security monitoring system is designed by integrating the interdigitated electrode-based triboelectric sliding sensor with a WIFI module and smart home APP. By installing the triboelectric sensor on the drawer and door, the subtle tremble of household equipment can be detected, demonstrating its reliability in home security monitoring. To solve the problem of poor sensitivity caused by hard contact electrification, Liu *et al.* designed a ferrofluid-based triboelectric tactile sensor (FTTS) with a wide detection range (390 kPa) and ultrahigh sensitivity (21.48 kPa^{-1}).[122] As shown in Fig. 9c, a personalized password lock is further demonstrated based on the FTTS. By controlling the different sequences and pressure applied on the relevant FTTS unit, the double protection of the password lock can be formed. The design of this password lock may improve the level of security protection and has great application potential in smart homes, IoT, and other fields.

Security monitoring for property and user information plays an important role in the smart home system. To further improve the aesthetic and practicability of home facilities, Shi *et al.* reported a natural wood-based triboelectric self-powered sensor (WTSS).[101] The WTSS shows superior sensitivity, stability, and flexibility, which can be easily integrated with household facilities for constructing a self-powered intelligent door lock system. As shown in Fig. 9d, the corresponding sensing units can generate an output signal when touched by the person's finger. Through multichannel data acquisition and signal processing, the touch code sequence with personal characteristics can be analyzed to realize identity recognition. Moreover, a self-powered floor monitoring system was also constructed for gait recognition by embedding the WTSSs on the wooden floor. Textile materials are also widely used in the home environment. Combining TENGs with traditional textiles will give birth to self-powered electronic textiles. Dong *et al.* reported a TENG-based electronic textile with high flexibility, shape adaptability, and structural integrity for biomechanical energy harvesting and pressure sensing by utilizing the 3D five-directional braided structure (Fig. 9e).[102] Additionally, a self-powered identity recognition carpet was fabricated to maintain internal security and prevent foreign invasion. When a person walks through the carpet, three judgment states will be displayed on the interface, and only those with the correct password can successfully pass the identity authentication to enter. Bai *et al.* also developed a membrane-based triboelectric sensor (M-TES) for self-powered air pressure sensing.[123] As shown in Fig. 9f, the M-TES has a multilayered structure, and the latex film will swell and contract when air pressure increases or decreases. Furthermore, the voltage signal generated by contact separation motion can be directly used for pressure sensing, providing an effective way to detect air pressure changes. By integrating with simple circuits, a self-powered system was constructed for sensing heartbeat, respirations, and footsteps. These works provide a reliable and simple way to develop monitoring systems for home security.

5. Conclusions and perspectives

Owing to its advantages such as high verification accuracy, large population coverage, and difficulty in duplicating or forging, biometric authentication has been widely used in the security field. In this review, we systematically summarised the recent progress in TENGs for self-powered biometric authentication and security monitoring. By converting the mechanical energy from human motion into electrical signals, the triboelectric self-powered sensors can be used to recognize five types of biometric characteristics, including sliding behavior, handwriting behavior, keystroke dynamics, gait characteristics, and voice characteristics. After appropriate structural design, the TENG-based self-powered sensors can be integrated with personal electronics to realize strong security in current authentication systems without significant modification. In addition, the applications of self-powered systems based on the TENG technology in individual electronics authentication and home security are also summarized. This novel concept of the TENG-based self-powered monitoring system may have a large number of potential applications in next generation security networks and smart electronics.

To improve the applicability of the TENG-based self-powered sensors in biometric authentication and security monitoring, potential challenges and opportunities for future research are also analyzed and discussed.

1. Sensing capability. As a self-powered sensing technique, its sensing sensitivity depends on the output performance of the TENG. To improve the output signal, various approaches including improving the surface charge density by introducing a micro/nanostructured contact surface or modifying materials, designing an innovative structure, and improving contact intimacy would be promising choices. Additionally, to improve the sensing capability, TENG-based self-powered sensors can be integrated with other sensing techniques to develop hybrid sensing devices.[124]

2. Durability and stability. For practical application, it is essential to improve the long-term stability of the TENG-based self-powered sensors. The first solution is to develop materials with robust mechanical durability for fabricating TENGs. Research about chemical modification and composite materials could be helpful. Given the operation of the TENG depends on environmental conditions, the second solution is designing a novel analytical sensing method that is independent of the signal intensity of the TENG.

3. Environmental influence. The biodegradability properties of materials are highly valued due to their medical and environmental benefits. At present, most of the materials for fabricating TENGs are non-degradable synthetic polymers, which may cause serious environmental pollution. In this context, developing renewable, biodegradable, and high-performance TENGs can be a good choice.[125] In addition, disposable self-powered sensors with low cost and no environmental impact would be a promising research direction.

4. Biocompatibility. Biocompatibility plays an important role in biomaterials because it ensures that the material is safe

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and compatible with living tissues or organisms.[126,127] Since triboelectric self-powered sensors may come into close contact with the human body, it is necessary to develop biocompatible triboelectric sensors for biometric authentication and security monitoring.

5. Big data analytics. By combining with cloud computing and artificial intelligence technologies, TENG-based big data analytics could be developed for automatically analyzing the collected data and providing higher sensing accuracy. Based on TENG-based big data analytics, intelligent biometric authentication systems can be built for broader application areas with a higher level of security.

6. System integration. In order to realize multiple functions simultaneously in future practical applications, researchers can focus on the perspective of sensor system integration and realize smart applications by combining remote control and machine learning. Moreover, by developing circuits integrated with other modules in sensor systems, the self-powered operation of the entire module can be realized. This will facilitate the widespread use of TENGs in wireless sensing networks.

Author contributions

J. Luo and W. Mai conceptualized, wrote, and edited the manuscript. X. Shi and K. Han wrote and edited the manuscript, as well as prepared figures. Y. Pang wrote and edited the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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