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Assistive devices for the people with disabilities enabled by triboelectric nanogenerators

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Abstract

According to data released by the World Health Organization, more than one billion people in the world experience some form of disability, in which they face all kinds of inconveniences. As a practical tool to help people with disabilities participate in social life, assistive devices for the people with disabilities play an important role in their daily lives. As an effective electromechanical signal conversion technology, triboelectric nanogenerator (TENG) has been successfully applied to various types of biosensors. This review aims to provide an overview of the development of assistive devices for the people with disabilities based on TENG with five categories: hearing, vision, pronunciation, gustation and limb/joint, according to the classification method of the impaired part. Meanwhile, a human–computer interaction system for the people with disabilities is also investigated. Finally, the prospect and potential challenges of this new field are discussed.

1. Introduction

According to data released by the World Health Organization, more than one billion people in the world live with a disability, including hearing, visual, pronunciation, physical, etc. People with disabilities can face multiple inconveniences, barriers, and dangers as a result of their health conditions [1, 2]. This corresponds to about 15% of the world's population. As a practical tool to help the people with disabilities participate in social life, assistive devices for the people with disabilities play an important role in their daily life [3].

At present, most electronic assistive devices for people with disabilities require battery power. However, due to the limitations of the battery industry, the battery itself often occupies most of the space and weight of such equipment, which is not conducive to the miniaturization and portability of the appliance, and even increases the burden on people with disabilities to a certain extent, and will cause the environment problems, etc [4, 5]. Therefore, it is of vital importance to realize the self-powered electronic assistive devices for people with disabilities and to add convenience to the daily life and rehabilitation monitoring for them.

In 2012, Wang *et al* proposed the triboelectric nanogenerator (TENG) as a self-powered technology for various sensors and energy harvesting devices [6]. For example, TENG has been successfully applied in the health and medical field as implantable medical sensors [7–13], biosensors [14–22], health monitoring sensors [23–31] and so on [32–37]. In addition, TENG-based energy harvesting devices have successfully harvested abundant biomechanical energy in the human body, such as heartbeat [9, 38, 39], breath [40], body motion [41–46] and so on [47–56]. This kind of device has the advantages of lightweight, high flexibility, stretchability, simple manufacture and low cost. It can directly contact the surface of human skin or organs for energy harvesting and health monitoring, and has been applied to the field of assistive devices for the people with disabilities.

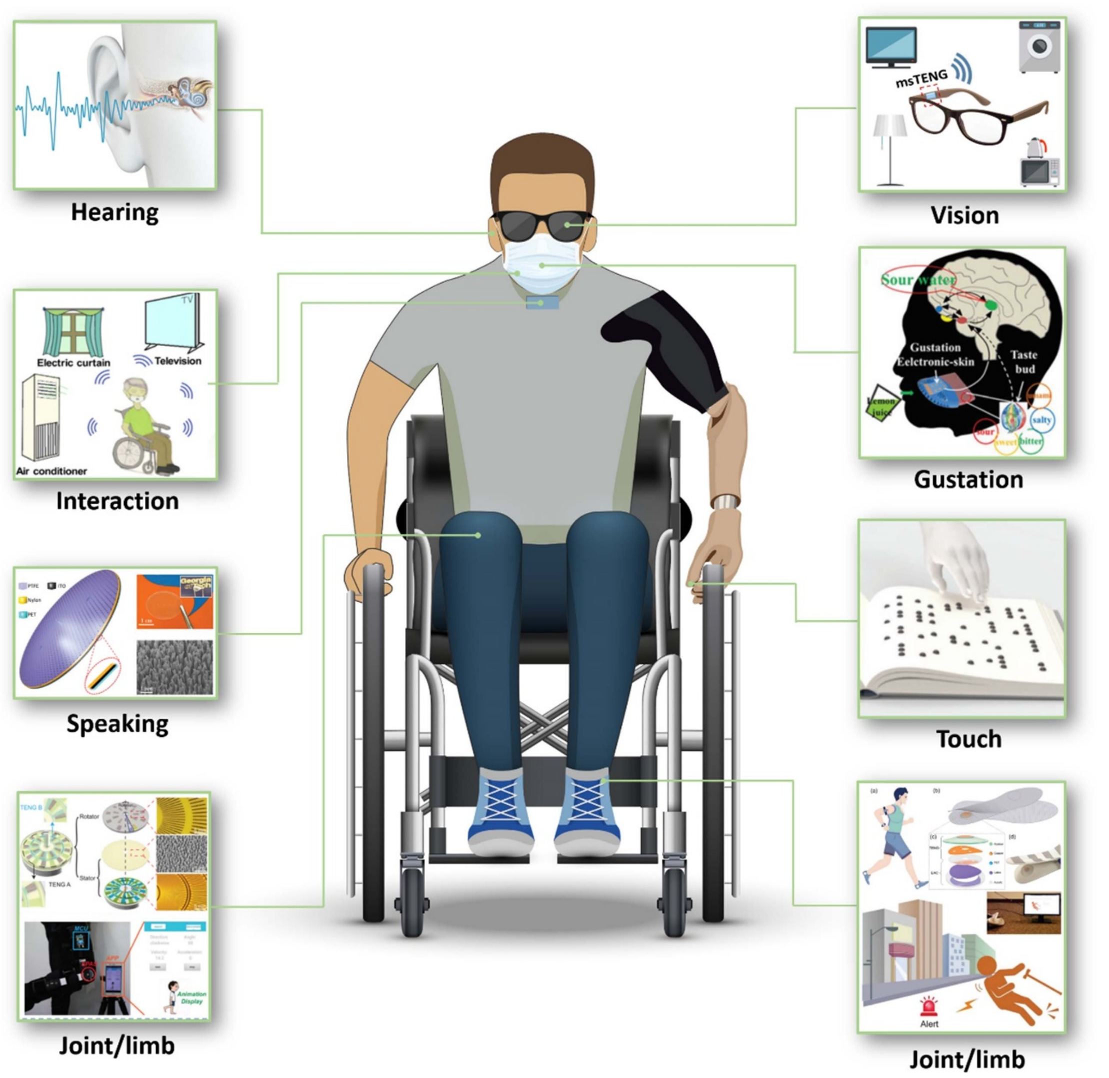

Figure 1. An overview illustration of assistive devices for the people with disabilities enabled by triboelectric nanogenerators (TENGs). Reprinted from [57], Copyright (2019), with permission from Elsevier. [58] John Wiley & Sons. [© 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim]. [59] John Wiley & Sons. [© 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim]. Reproduced from [60] with permission of The Royal Society of Chemistry. [61] John Wiley & Sons. [© 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim]. [62] John Wiley & Sons. [© 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim].

This review aims to overview the development of TENG-based assistive devices for the people with disabilities, covering the most typical categories as is shown in figure 1. In order to clarify the correspondence between the assistive devices for the people with disabilities and the classification of the damaged part, the review tends to classify the assistive devices into five categories: hearing impairment, vision impairment, pronunciation impairment, gustation impairment and limb/joint impairment. In addition, a human-computer interaction system for the people with disabilities has been also investigated. This article first introduces the theory and working mode of TENG, and then introduces TENG-based assistive devices for the people with disabilities according to the above categories, and finally, the prospective to the future and the potential challenges in this area are described.

2. Triboelectric nanogenerator

2.1. Theory of TENG

The triboelectric effect is a kind of electrification effect caused by contact [63]. When two objects with different abilities to gain or lose electrons come into contact with each other, the electrons are transferred from one object to the other, causing the two objects to carry equal amounts of different charges. The surface of a material that has a strong ability to gain electrons will attract negative charges. On the contrary, a surface of a material that has a strong ability to lose electrons will attract positive charges. The essence of triboelectric effect is the transfer of electric charge. The positive or negative charge of a material depends on the ability of two contacting materials to obtain electrons.The triboelectric effect widely exists in people's daily life. For a long time in the past, the triboelectric effect was regarded as a negative effect. For example, static electricity caused by triboelectricity will bring huge losses to industrial production, electronic equipment, and human life. Recently, Professor Zhong Lin Wang proposed the triboelectric nanogenerator. Its principle is based on the coupling of triboelectric effect and electrostatic induction effect, which can directly convert mechanical energy into electrical energy and turn negative effect into positive effect. It is widely used in the fields of energy harvesting and self-powered sensing.

The basic principle of TENG can be traced back to Maxwell's equation. Maxwell's equation is one of the most important equations in the field of physics. Maxwell introduced displacement current in Ampere's law to satisfy the continuity equation of charge. Professor Zhong Lin Wang extended the expression of the displacement current (Wang term), the term $\frac{\partial P_s}{\partial t}$ was introduced in Maxwell's displacement current for describing the theory of nanogenerators, where P_s is the polarization density introduced by surface electrostatic charges owing to contact-electrification or piezoelectric effect [64]:

$$\varepsilon\nabla \cdot E = \rho - \nabla \cdot P_s \tag{1}$$

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

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

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

$$J_D = \frac{\partial D}{\partial t} = \varepsilon\frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t}. \tag{5}$$

Note that E is the electric field, B is magnetic induction, H is magnetic field intensity ρ is the distribution of free charges in space, J is the density of free conduction current density in space as a result of charge flow, t it time, D is the electric displacement vector, based on which Maxwell proves the equivalence of electricity and magnetism. As the theoretical origin of the TENG, Maxwell's displacement current (equation (5)) is caused by the time variation of the electric field plus a media polarization term. The addition of the P_s term to the electric displacement vector opens the application of Maxwell's equation in the field of energy and sensing. With the establishment of general theories and continuous improvement of materials and structures, TENG will reach new heights in the field of energy and sensing.

2.2. Working mode of TENG

In order to make more effective use of various mechanical energy in different environments, so that the TENG under different motion state can convert mechanical energy into electrical energy, the researchers established four working modes of the TENG: vertical contact-separation mode, lateral sliding mode, single-electrode mode and freestanding triboelectric-layer mode. These four basic working modes are the basis of all structures of TENG, and many different structures can be derived according to specific applications [15].

2.2.1. Vertical contact-separation mode

As shown in figure 2(a), two different materials are used as two friction layers, and conductive materials are deposited on the surfaces of these two friction layers as electrodes. Under the action of external force, the two friction layers contact with each other, the surface of the material will generate an equal amount of heterogeneous charges. When the external force is released, the two friction layers begin to separate, at this time, an electric potential difference is generated at the interface, free electrons flow from an electrode to another driven by the electrostatic field. When the two friction layers are in close contact again, this potential difference will disappear. When applying and releasing mechanical force to this working mode TENG, periodic voltage output will be obtained [65–67].

2.2.2. Lateral sliding mode

As shown in figure 2(b), similar to the vertical contact-separation mode, two different materials are used as two friction layers, and conductive materials are deposited on the surfaces of these two friction layers as electrodes. When the two friction layers are in complete contact, the charges are in equilibrium and there is no potential difference at the interface. When an external force is applied to the two friction layers in the

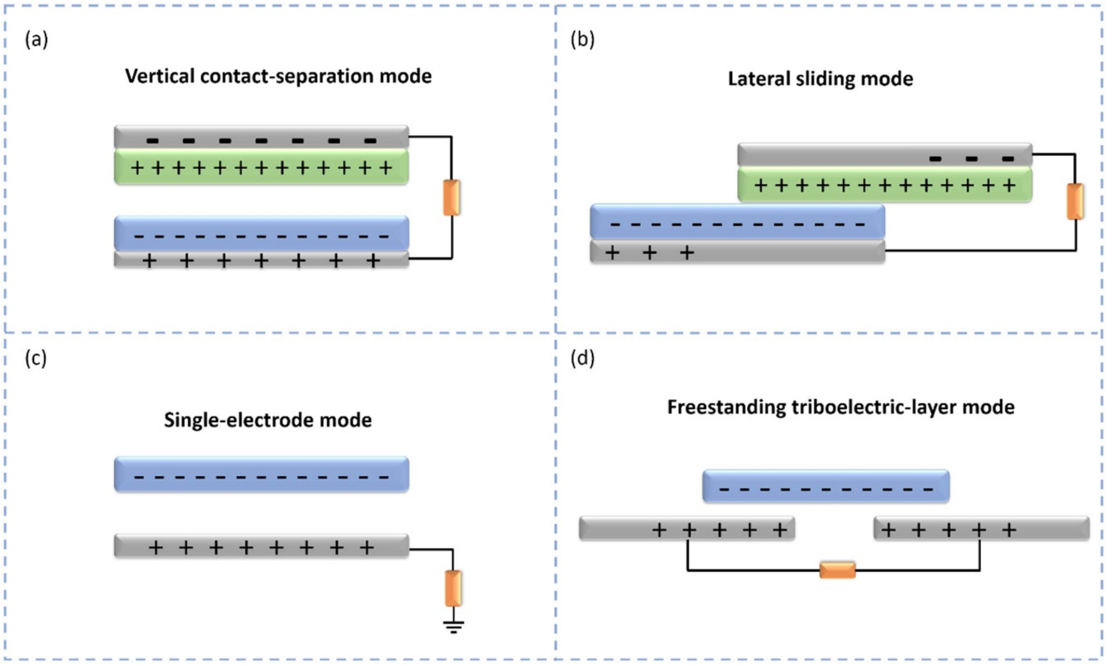

Figure 2. Four fundamental working modes of TENG. (a) Vertical contact-separation mode. (b) Lateral-sliding mode. (c) Single-electrode mode. (d) Freestanding triboelectric-layer mode.

horizontal direction of the relative displacement, the electrons on two electrodes are driven to flow by the triboelectric charges. A periodic voltage output can be generated by sliding the two friction layers periodically when they are completely in contact and completely separated. Compared with the previous working mode, the voltage output of this mode is more impressive due to more effective contact [68, 69]. This working mode can also be extended to other structures, such as disc rotation and so on.

2.2.3. Single-electrode mode

As shown in figure 2(c), the single-electrode mode TENG consists of a movable friction layer and an electrode. When the friction layer and the electrode layer are in close contact, the surface of two kind of materials will induce the same amount of different kinds of charges. When the friction layer leaves the electrode layer, the field distribution of local electric will change. In order to adapt to potential changes, electrons will flow between the electrode and the ground. Periodic contact and separation of friction layer and electrode layer can generate periodic voltage output [70, 71]. This working mode can also be extended to a single-electrode-sliding mode.

2.2.4. Freestanding triboelectric-layer mode

As shown in figure 2(d), Two unconnected symmetrical electrodes are respectively plated under the dielectric layer (charged body), and the width of the electrodes is consistent with the width of the moving object. The reciprocating movement of this charged body between the two electrodes will cause an asymmetric charge distribution on the surface of the material. Electrons will flow from one electrode to the other, in an effort to balance the change of electric potential difference [72, 73]. Due to this structure, there is no direct mechanical contact between the dielectric layer and the symmetrical electrode, which can greatly reduce the wear of materials and prolong the service life of TENG.

3. Assistive devices for the people with disabilities based on TENG

3.1. TENG-based devices for the hearing impaired

There are many people experiencing from hearing impediments. Sensorineural hearing loss is one of the most typical hearing disorders caused by the damage of hair cells of the Corti in the cochlea (figure 3(a)) [74]. Cochlear implant is a device that converts sound into coded electrical signals [75]. In recent years, with the development of electronic technology and materials science, many researchers have been studying various kinds of cochlear implants [76–78], such as piezoelectric based sensors [79–82]. Such devices can convert sound waves into specific electrical signals, which have a wider frequency response and frequency selectivity. However, the output signal of piezoelectric sensors is lower and the production cost is

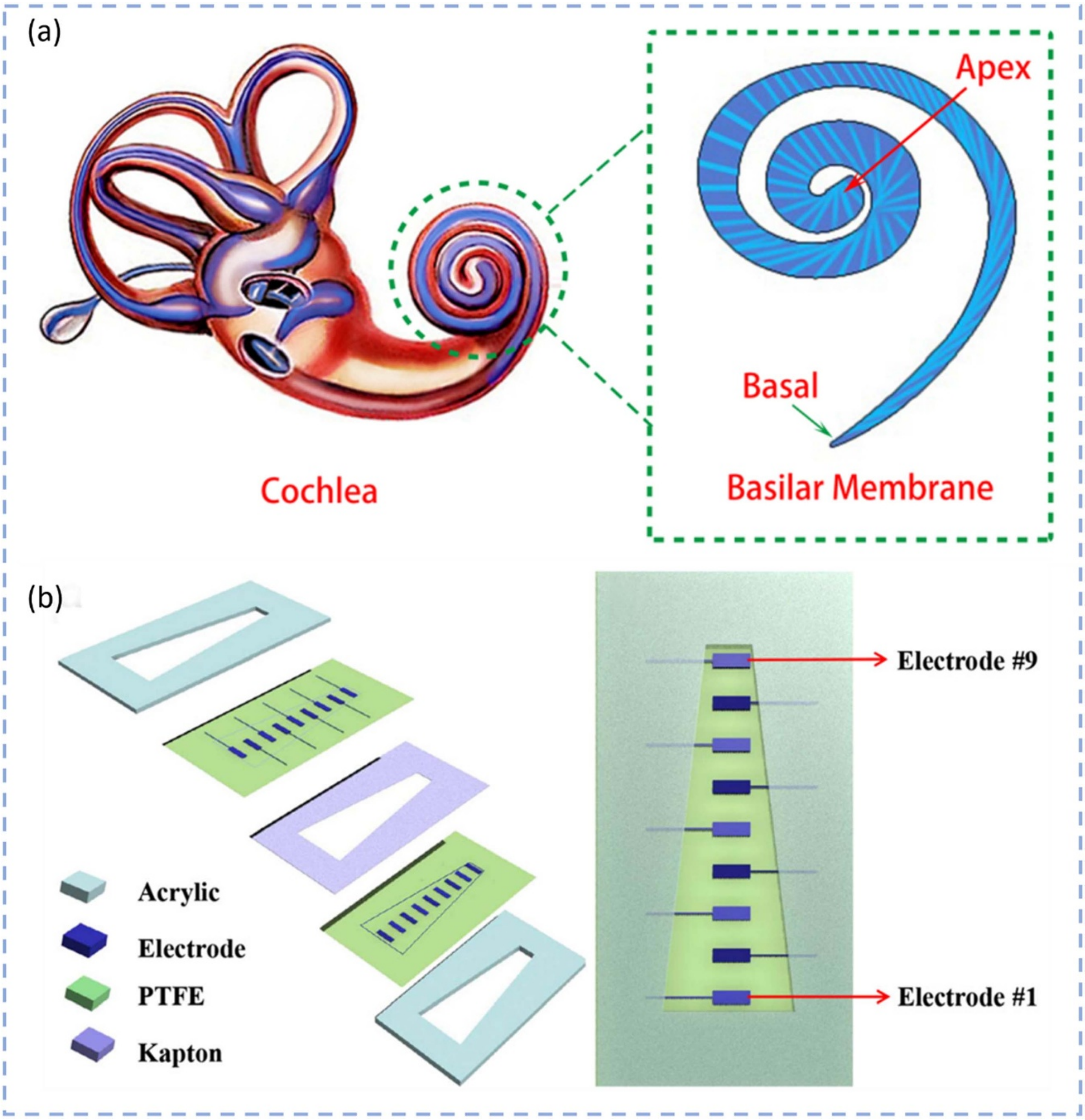

Figure 3. TENG-based devices for the hearing impaired. (a) Conceptual schematics of the cochlear and the basilar membrane. (b) Structural design of the bionic cochlear auditory sensor for frequency selectivity [74]. Reproduced from [74]. CC BY 4.0.

higher. Therefore, a sensor that is simple to manufacture, low in cost, and has high sensitivity and high signal-to-noise ratio is needed to solve these problems.

Liu *et al* reported a novel bionic cochlear auditory sensor enabled by triboelectric nanogenerator, which can transform acoustic signal to electrical signal directly, and realized the function of frequency selectivity [74]. As shown in figure 3(b), the sensor imitates the basement membrane of the cochlea and consists mainly of a trapezoidal polytetrafluoroethylene (PTFE) film and nine small rectangular silver electrodes. The external sound signal makes the PTFE film resonate, contacting and separating from the electrode layer to generate a voltage signal. Different position on the trapezoidal structure has its own specific response frequency range from 20 to 3000 Hz.

Guo *et al* recently reported a self-powered triboelectric auditory sensor (TAS) for an external hearing aid in bionic robot also in assistive devices for the people experience from the hearing impediments [83]. The core structure of the TAS consists of a fluorinated ethylene-propylene (FEP) film with Au electrode, a 100 μm thick spacer, and a film with Au electrode. FEP membrane has a porous structure to make the sound wave across, the outside of the TAS is an acrylic board for fixing. When a certain frequency of sound wave passes through, the Kapton film and the FEP film in the device will contact and separate at a certain frequency, thereby generating electrical signals. The reported TAS has achieved an ultrahigh sensitivity of 110 mV dB^{-1} and a widest ever frequency response from 100 to 5000 Hz. In most cases, the hearing impaired is deaf to only one or several specific frequency areas. The advantage of TENG based sensors is that they can be designed to meet a variety of requirements using a variety of structures and do not require complex signal conversion circuits, thus minimizing the overall system cost. Through the structural design, the device can work in the corresponding resonant frequency region, and the signal spectrum can be converted and analyzed to repair the sound information. This work demonstrated the potential of TAS as a cochlear implant or a hearing aid.

3.2. TENG-based devices for the vision impaired

Studies have revealed that more than 80% of external information reaches the brain through vision, however there are about 39 million blind people worldwide [84]. Because of impaired vision, the blind cannot get information efficiently like the normal. They rely on tactile sense, hearing and residual vision to obtain information around the environment. The sense of touch, which is a comprehensive function of pressure, soma esthesia in the hands and skin, is the most important way for visually impaired people to perceive the world and obtain information from outside [85]. For text messages, the blind usually gets them by touching Braille contacts with finger, however Braille books are immutable and thick. Currently, some researchers have studied Braille display devices, most of them are based on electromagnetic, piezoelectric or electrical stimulation [86–88]. However, these devices have complex structures or require high-voltage power supply drive, which is potentially dangerous. Therefore, a safe, efficient, simple and low-cost braille display device is needed.

Recently, Qu *et al* demonstrated a refreshable Braille display system based on dielectric elastomer and TENG [61]. Dielectric elastomer is used as an actuator, and TENG is used as an actuating source. Through the IPC etching treatment on the Kapton surface of the friction layer of TENG, its output performance is effectively improved, so that it is enough to actuate the dielectric elastomer membrane. As is shown in figure 4(a), the Braille display system consists of three parts: TENG, control module and Braille display module. Researchers used dielectric elastomer membrane to fabricate the Braille dots for their display. They are raised and lowered through the combined effect of high voltage and air pressure inside the display module. By integrating an electronic switch into display system, researchers turned a single six-dot Braille module from a static device into a dynamic device. Dielectric elastomer is a good combination with TENG, compared to commercial high-voltage power supply, TENG has the advantage of good safety. By touching the contacts of the Braille display system, the blind can obtain Braille information. This provides the possibility for the realization of portable, safe and low-cost Braille e-books (figure 4(c)).

3.3. TENG-based devices for the speech impaired

Language is the main method of our daily communication. However, many people with speech impairment, cannot communicate effectively with others nomrally. As a result, they may have social fear and low self-esteem, stand the pain of the body at the same time to the torture of soul. Speech impairment is a functional disorder of the vocal organs, which is caused by the shortening of the tongue muscle belt, cleft lip and palate, and throat muscle incoordination. In order to alleviate the pain of speech disorders, the development of speech rehabilitation assistive devices is of great significance. The auxiliary vocalization methods include esophageal/tracheal vocalization, electronic larynx, auto-pneumatic artificial larynx, etc [58, 89, 90]. However, they have certain defects. For example, the esophageal/tracheal sound generator needs to be inserted into the esophagus/trachea, which can cause infection; the precision of the electronic larynx is low and requires the patient to hold it. In addition, so far, most wearable pressure sensors are based on the principle of capacitance [91], piezoelectricity [92, 93] and resistivity [90] changes. Although each has its advantages, the structure is generally complicated and requires an external power supply. Therefore, for the speech impaired, their ideal speaker is a wearable, hands-free and self-powered.

Yang *et al* proposed a self-powered bionic membrane sensor (BMS) for voice recognition [58]. As is shown in figure 5(a), polyethylene terephthalate (PET) film is used as the supporting substrate, a layer of indium tin oxide (ITO) coated nylon film is covered on the PET substrate. Nylon and ITO are used as friction layer and electrode layer respectively, and PTFE film with nanostructure is used as another friction layer. A PTFE membrane is tented outwards at the level of the tip of an umbo, and PET is used as the material of umbo. The height of the umbo will determine the pressure detection limit and detection range of the sensor. The tapered structure between PTFE and nylon forms a cavity, and two circular holes with a diameter of 0.5 mm penetrate through the three layers of PET, ITO and nylon to make the tapered cavity merge with the surrounding air. BMS has fast response time (less than 6 ms), wide dynamic range (0.1 Hz to 3.2 kHz) and higher sensitivity (51 mV Pa^{-1}). As shown in figure 5(b), BMS is attached to the throat of the experimenter as a self-powered laryngeal microphone. When the experimenter sounds with the throat, BMS presents the sound information in the form of voltage, as shown in figure 5(c). Fourier transform is applied to the signal to present the sound information of 45–1500 Hz. It can be used in the field of speech recognition, as well as in the field of wearable medical care, providing convenience for people with speech impairments without throat damage.

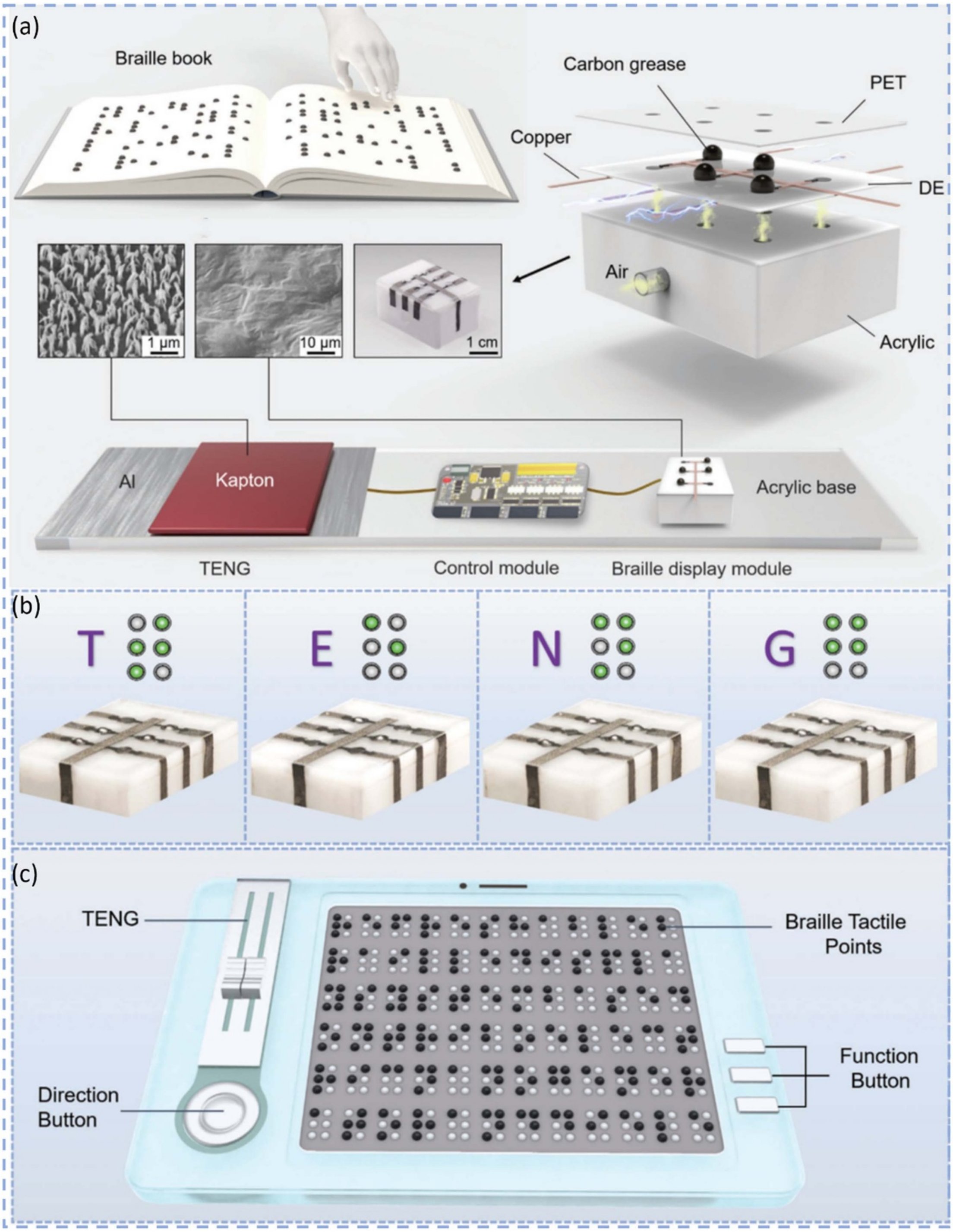

Figure 4. TENG-based devices for the vision impaired. (a) Design of the Refreshable Braille Display System. The system consists of the TENG, Braille display module, and the control module. (b) Braille letters of 'T,' 'E,' 'N' and 'G' displayed by Refreshable Braille Display System. (c) Refreshable, cost-effective, and safe Braille e-book for the blind. [61] John Wiley & Sons. [© 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim].

Sensors in direct contact with human skin should show good flexibility and stretchability, and have the ability of high signal quality, while rigid sensors cannot fit human skin well. It is an important task to improve strain sensor so that it has all the characteristics mentioned above. In order to better fit the contour of the throat, Hwang *et al* proposed a highly stretchable, sensitive and transparent sensor based on the multifunctional silver nanowires (AgNWs)/poly(3,4-ethylenedioxythiophene): polystyrenesulfonate (PEDOT:PSS)/polyurethane (PU) nanocomposite, and integrate TENG and supercapacitor as energy supply and storage for amplifier (figure 5(d)) [94]. Attach the device to the throat as an autonomous invisible conformal sensor to monitor the motion of a person's throat, such as breathing, coughing, drinking, swallowing and eating. It has been used universally. This has important implications for people with language

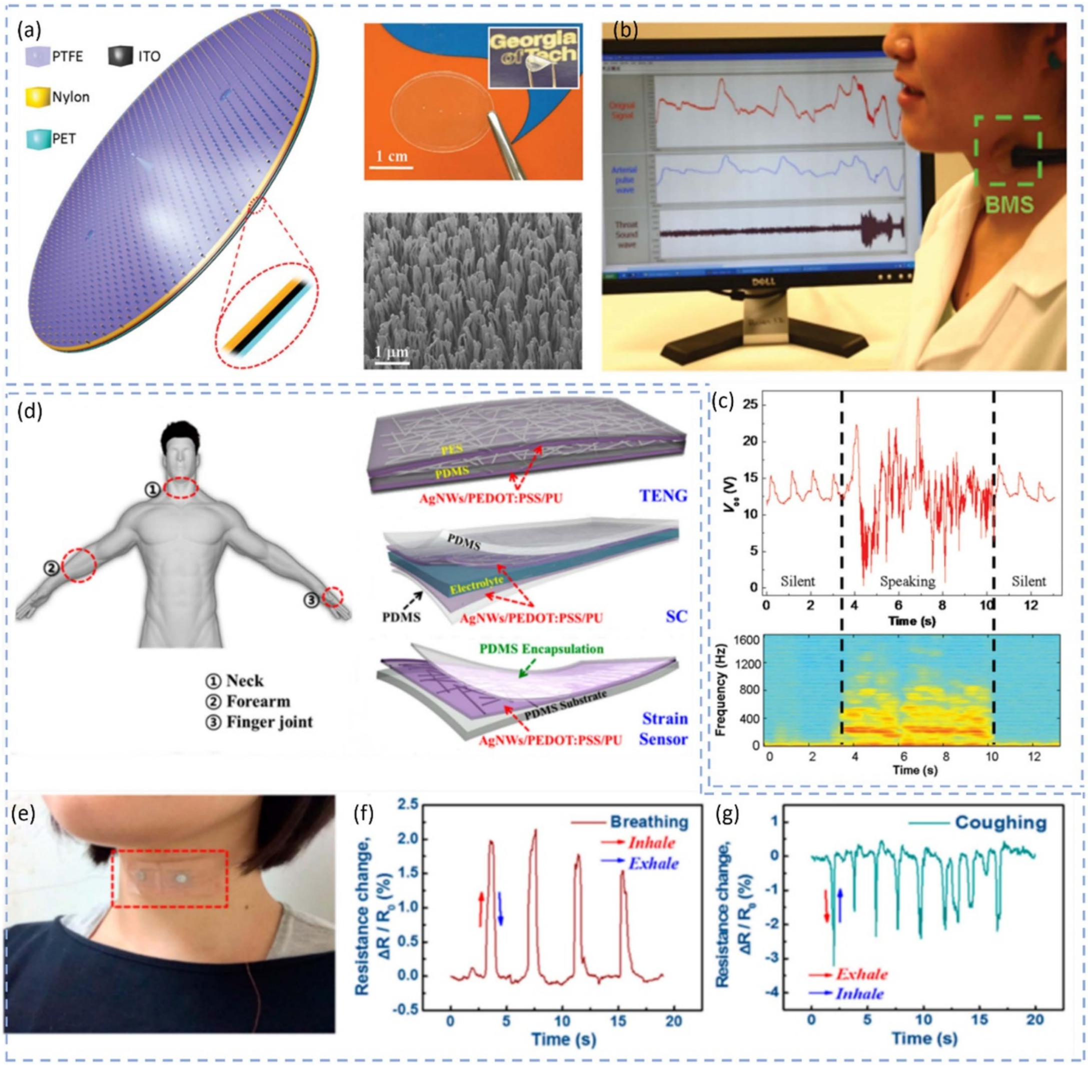

Figure 5. TENG-based devices for the speech impaired. (a) Structural design of the bionic membrane sensor (BMS). (b) A picture showing the BMS attached to the participant's neck acting as a self-powered throat microphone. (c) The real-time voltage output in response to the throat vibration during speaking, and corresponding Fourier transform of the acquired output voltage, the frequency components spanning from 45 to 1500 Hz. [58] John Wiley & Sons. [© 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim]. (d) Schematic descriptions of the TENG, supercapacitor (SC), and strain sensor. (e) Monitoring of throat motion. ((f), (g)) Resistance change of the strain sensor, measured by SC charged by TENG, during breathing and coughing. Reprinted with permission from [94]. Copyright (2015) American Chemical Society.

impairments, as the sensors can alert themselves and those around them in an emergency. In addition, it can also be used in other fields, including electronic skin, soft robot, human–computer interaction and so on.

3.4. TENG-based devices for the gustation impaired

Feeling plays a vital role in the interaction between human beings and the external environment [95]. Taste buds are special receptors on the tongue, that can detect and transmit gustatory information to the brain. Artificial taste electronic skin can recognize drinks, transmit biochemical sensing signals to the brain and participate in taste perception, which may be helpful for the gustation impaired. Recently, surface acoustic wave sensors and cell substrate impedance sensor have realized the substitution of taste [96]. However, these devices usually require large external power supply, which increases the production cost and limits the promotion of integrated flexible artificial taste system [97].

To this end, Zeng *et al* proposed a self-powered biosensing enabled by triboelectrification and biochemistry, for the detection of pH value and alcohol concentration [60]. The biosensing can overcome the technical gap in power supply, beverage chemical state detection, signal transmission and other aspects of neural bionics, the outputting current signal carries the sensory information obtained from taste buds and transmits it to the brain, as shown in figure 6(a). The sensor is composed of three parts: polydimethylsiloxane (PDMS) layer, Cu electrode and polypyrrole (Ppy) film, PDMS film is used as substrate and triboelectric material; photolithography patterned copper network is utilized as electrode and supporter to maintain Ppy;

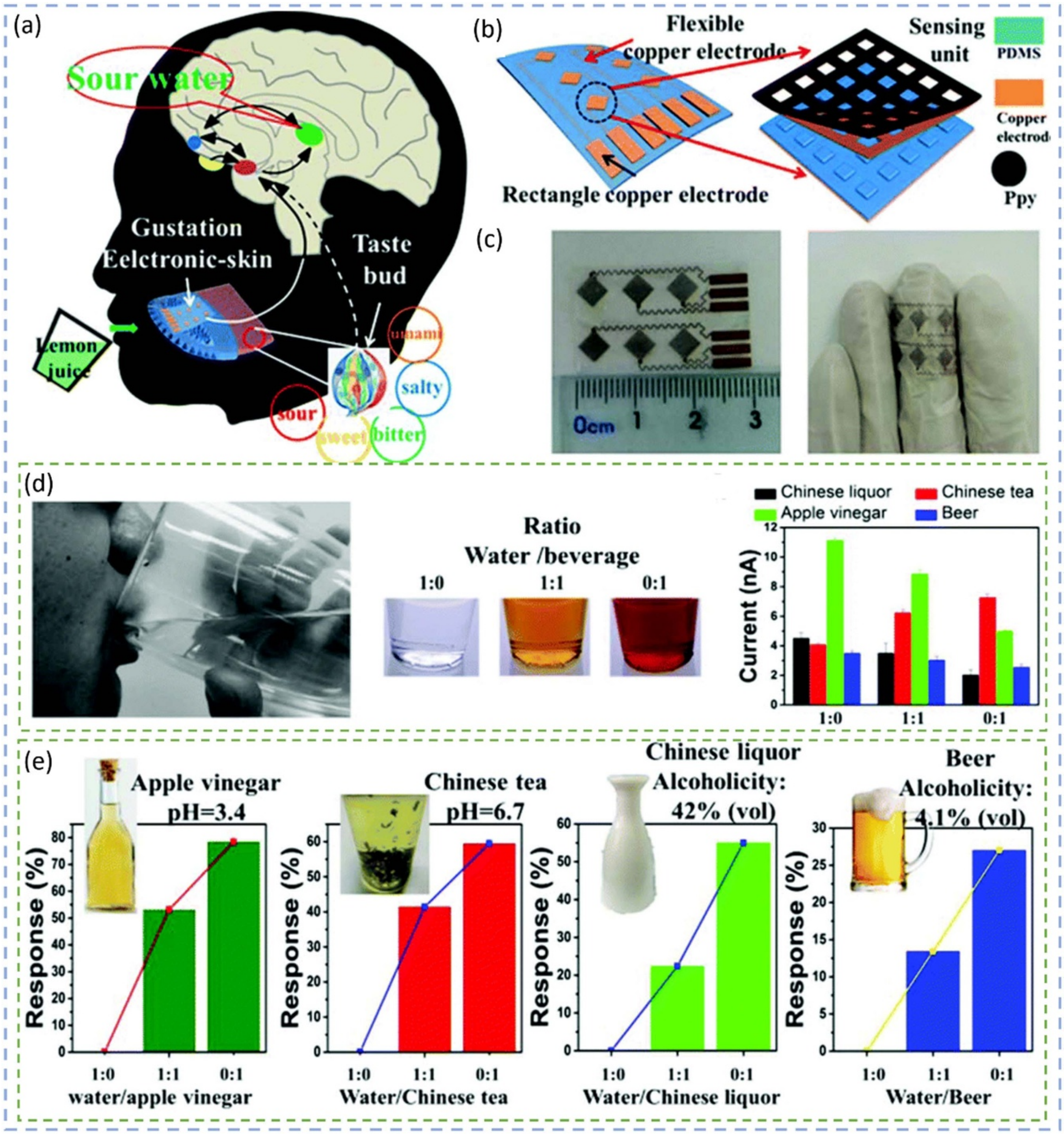

Figure 6. TENG-based devices for the gustation impaired. (a) An artificial gustation system (e-skin) for gustatory perception substitution without an external electricity source. (b) Basic structure of the e-skin. (c) Optical pictures of the e-skin. (d) The bio-chemical sensing performance of biosensing e-skin against four kinds of beverages. Reproduced from [60] with permission of The Royal Society of Chemistry. (e) The relationship between response and pH value (alcoholicity) of apple vinegar, Chinese tea, Chinese liquor and beer.

Ppy polymer film is used as triboelectric and sensing material, as illustrated in figure 6(b). Figure 6(c) shows that the sensor has good flexibility and transparency. The surface chains of Ppy will change in different pH and alcohol concentrations, resulting in different electron affinity for the Ppy surface. So that the output will be affected by the chemical state of the interface between Ppy and PDMS. Under acidic conditions, H^+ ions make the Ppy change to oxidation state and increase the electron affinity, which results in much lower output of the sensor. Under alkaline condition, OH^- ions make the Ppy change to the reduction state and decrease the electron affinity, causing the output of the sensor higher. Ethanol in the enzymatic reaction can be decomposed into ethanol and H^+ ions, therefore, with the concentration of ethanol in the solution increased, the output of the sensor decreased. The self-powered biosensing can detect common beverages, such as Chinese tea, apple vinegar, Chinese liquor and beer which diluted by adding different proportions of water, as shown in figure 6(d). Figure 6(e) proves that the sensor can taste various beverages without external power supply. This study provides a novel approach for developing artificial gustation sensor with low cost.

3.5. TENG-based devices for the joint (limb) impaired

With the rapid development of modern society, human health may be affected by the fast-paced life, and their joint (limbs) may also be injured by some accidents. For the joint (limb) impaired, rehabilitation accessory

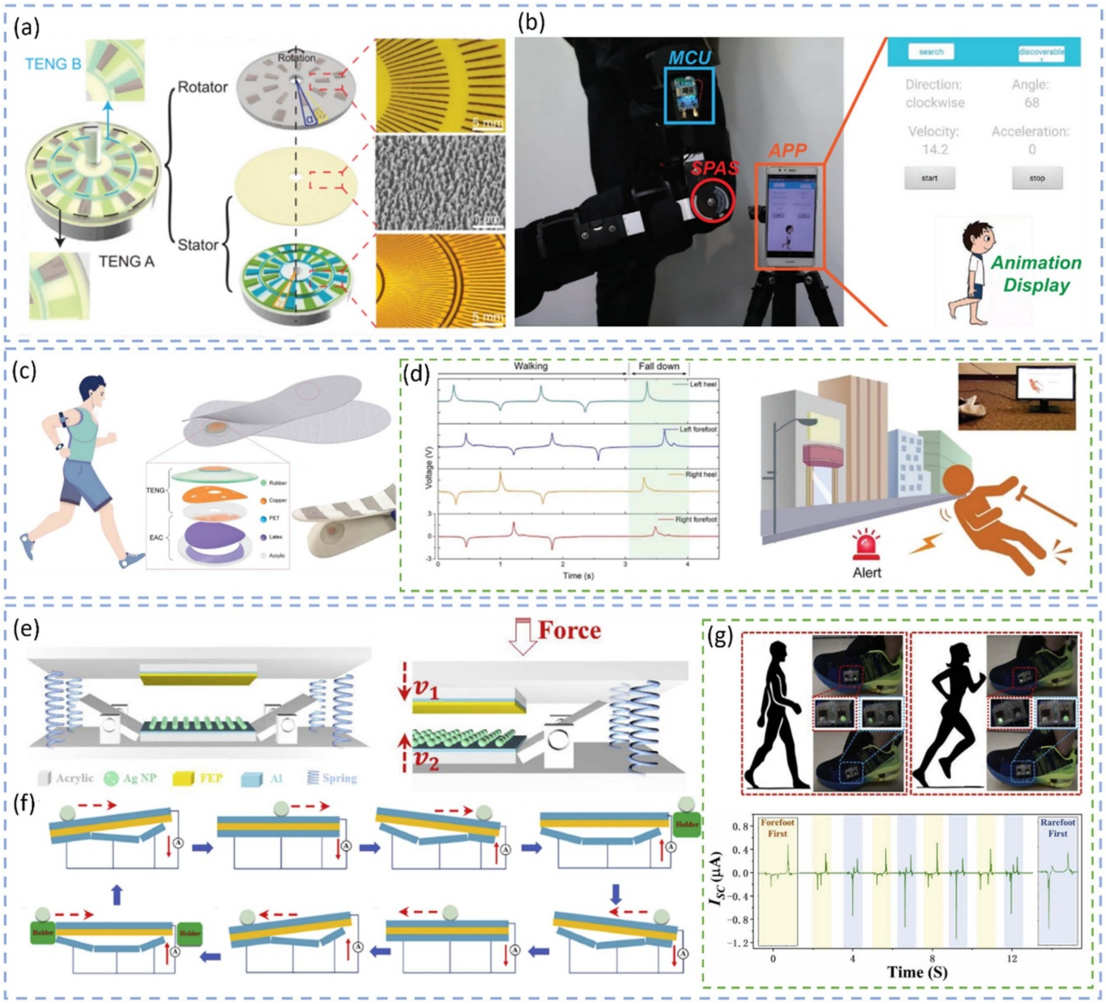

Figure 7. TENG-based devices for the joint (limb) impaired. (a) Detailed structural information of self-powered angle sensor (SPAS), which consists of two TENGs: the outer part is named as TENG A (indicated in black) while the inner part is TENG B (indicated in blue). (b) The application of SPAS to the recording of joints' flexion/extension angles. [59] John Wiley & Sons. [© 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim]. (c) The smart insoles are assembled into the shoes to serve as a self-powered gait monitoring system, and structural design of the TENG-based sensor. (d) Application of the smart insoles for warning of fall down. (e) Structure of seesaw structured triboelectric nanogenerator (SS-TENG). [62] John Wiley & Sons. [© 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim]. (f) Working mechanism and dynamic states of SS-TNEG. (g) Demonstration of SS-TENG by integrating LED circuit boards; Current signals of SS-TENG under forefoot strike and rearfoot strike. Reprinted from [106], Copyright (2019), with permission from Elsevier.

instrument and motion detection equipment are essential [95, 98–100]. However, these appliances are currently bulky and costly. In addition, the main strategy for powering motion sensors is to use batteries or power supplies, which have many disadvantages, such as limited lifetime, rigid structure, and environmental pollution [101–105]. Therefore, it is of great significance to explore new technologies of energy acquisition in human or environment, to realize self-power supply and to reduce the burden for the people with disabilities.

Towards this goal, Wang *et al* have reported a self-powered angle sensor (SPAS) which is based on two rotary contact-sliding mode TENG devices, with benefits of lightweight, thin thickness and low cost [59]. The SPAS consists of two coaxial parts, one is the rotator which mainly includes two groups of radially-arrayed freestanding electrodes made up of copper with different central angle, the other is the stator which consists of the electrification layer made of a Kapton film and two groups of interdigital electrodes made of copper. The SPAS could record angle data of the joints flexion/extension, and then transmit to the microprogrammed control unit, eventually, the vital motion parameters and status of joints could display real-time on the application (APP), as illustrated in figure 7(a). Figure 7(b) shows The SPAS paves a new approach for application for personalized orthopedic recuperation.

Accurate monitoring of human gait is essential for health assessment and early diagnosis, especially for the medical care of the elderly and injured. Abnormal gait may be an important predictor of disease risk. Towards this goal, Lin *et al* designed a smart insole for real-time gait monitoring with the novel air-pressure-driven structure based on a TENG, of which the structure is shown in figures 7(c) and (d) [62].

This sensor consists of an elastic air chamber and a TENG which utilize the air pressure within the sealed device to achieve the contact and separation events between the two triboelectric layers. This sensor could monitor and analyses the injury condition and rehabilitation of the patient and also be used as an emergency fall detection alert system for the elder, patients and the people with disabilities.

Lin *et al* have proposed a seesaw structured TENG (SS-TENG) for monitoring the movement of passing objects and human foot [106]. This device based on contact-separation working mode is composed of a top triboelectric unit and two seesaw-structured linkages that link with a bottom triboelectric unit by flexible connectors, as shown in figure 7(e). When the top triboelectric unit is driven downward by the external force, a seesaw-like linkage will be triggered to lift the bottom triboelectric unit and drive it to move upward, which means that both friction surfaces participate in the relative motion and improve the moving speed, as illustrated in figure 7(f). Figure 7(g) shows the device could be installed in common shoes for bio mechanical energy collection and different states of human motion sensing due to the asymmetrical structure. Such devices would be of great help to persons with physical disabilities.

3.6. TENG-based devices for human-machine interaction

Nowadays, smart devices (computers, household appliances, sensors, etc) have brought tremendous convenience to people's daily lives, and people are increasingly inseparable from these devices [107]. Using these devices has become a fundamental human skill. At present, human–computer interaction devices mainly rely on human physical movement or voice interaction. However, due to physical or language defects of some disabled people, these traditional human–computer interaction methods are not friendly to some handicapped. The artificial interaction system designed for the people with disabilities is to use the surviving physical functions, such as part of the limbs, blinking, blowing/inhaling, and electromyographic signals, etc, through computer coding, to realize the control of the environment [108–110]. Through these assistive devices, the people with disabilities can have a convenient, safe, and healthy barrier-free living environment to the maximum extent.

Zhang *et al* proposed a self-powered sensor driven by breathing, which interactively transmits control commands for human-machine interaction through breathing. The senor is based on a PET film with a flexible nanowire structure as a friction layer and copper as an electrode layer (figure 8(a)) [57]. Its principle is shown in figure 8(b), which is a single-electrode TENG. It can obtain the mechanical energy of the airflow from the human breath and generate corresponding electrical signals. The researchers connected the sensor to the signal processing module and the wireless transmission module, converted real-time breathing (blow and exhale) into command signals, and successfully controlled furniture such as lights and fans without relying on body movements or language (figures 8(c) and (d)).

Pu *et al* proposed a hands-free control and typing system through the micromotion of eye blink. This system is based on a single-electrode mode TENG which is called mechnosensational TENG (msTENG) [112]. It has a multi-layer structure, in which PET film is the substrate, FEP film is the friction layer, ITO attached to FEP is the back electrode, and natural latex which will contact the skin near the eyes as another friction layer. Compared with the traditional electrooculogram signal (∼1 mv), this sensor can effectively capture blinking motion and obtain a voltage (∼750 mv) which is 750 times higher than that of electrooculogram. Similarly, adding signal processing and transmission modules to control furniture. Moreover, the system realizes the operation of typing by blinking. There is a grouped keyboard on the operation interface, the cursor will move quickly at a certain frequency, and the required characters can be confirmed by blinking. The furniture control system and typing system based on msTENG provide a low-cost and convenient human-computer interaction solution for the people with disabilities, especially for the limb impaired, which has important practical value.

Anaya *et al* proposed a none contact sensor, based on free-standing configuration TENG. Ecoflex and PEDOT: PSS-based film is the key to the sensor as is shown in figures 8(e) and (f) [111]. Due to the triboelectric interaction between the two elements in motion, voltage is generated in a separate conductor by non-contact electrostatic induction. In addition, the researchers used circuits and python to realize human-computer interaction by blinking eyes, such as hands-free car control, drone control, and driver fatigue monitoring. TENG based sensors of this type are innovative in materials and structures, providing a novel design concept for intelligent sensor technology, human–machine interaction and promising applications in disability assistive tools.

4. Summaries and perspectives

This review systematically summarizes the research progress of TENG as an assistive tool (sensing) for the people with disabilities for the first time. As a new technology that can directly convert mechanical energy into electrical energy, TENG has been successfully applied to the fields of sound sensors, tactile sensors,

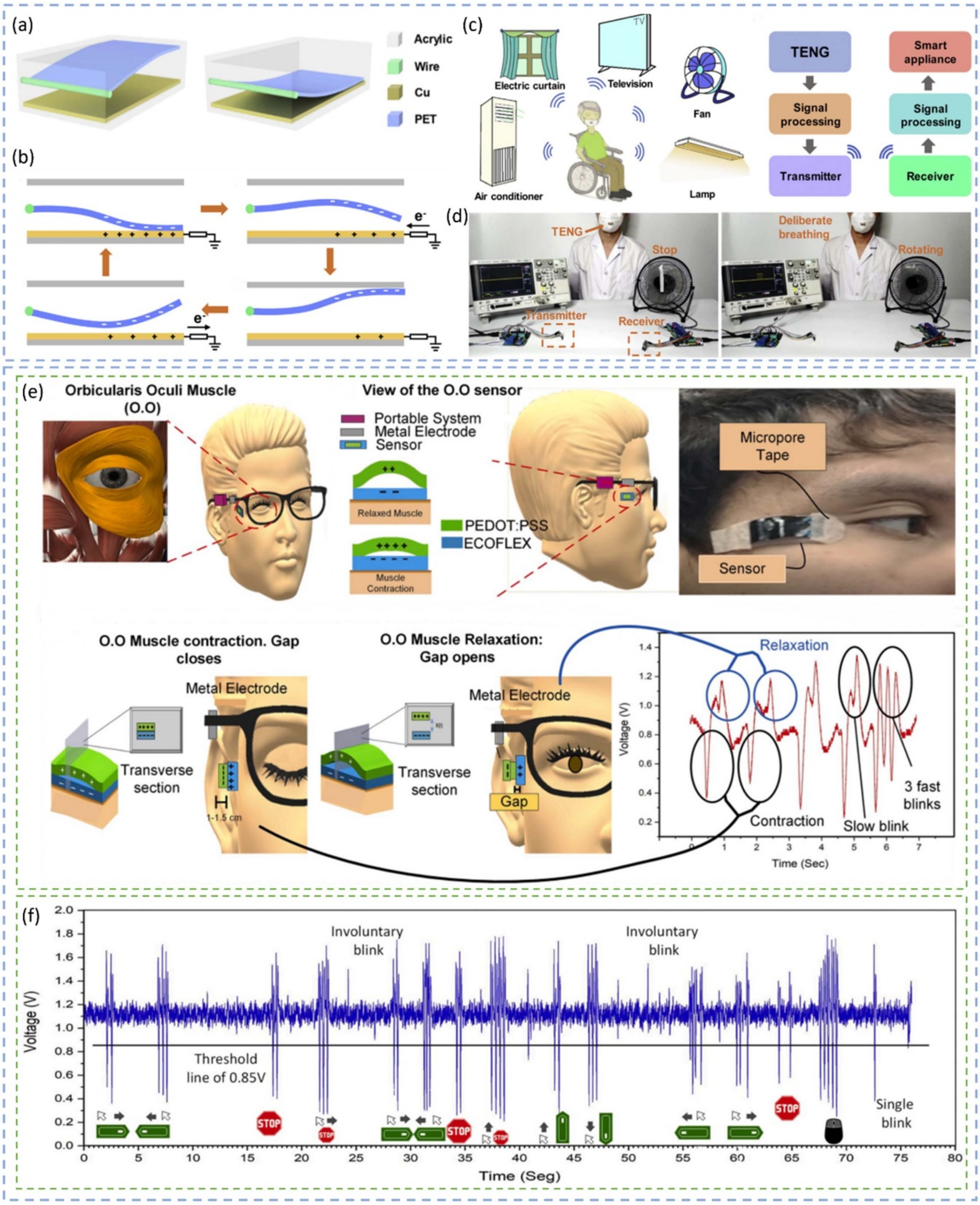

Figure 8. TENG-based devices for human–machine interaction. (a) and (b) Structure and working mechanism of the breath-driven TENG. (c) and (d) Sketch of a smart wireless human-machine interaction system based on the breath-driven TENG for controlling electrical equipment. Reprinted from [57], Copyright (2019), with permission from Elsevier. (e) and (f) The demonstration of a hands-free typing system to help people experiencing from physical disability to communicate with the world. The words on the screen are typed with eye blinking. Reprinted from [111], Copyright (2020), with permission from Elsevier.

wearable sensors, joint motion monitoring, and human–computer interaction, for people with a variety of disabilities. It provides a new choice of assistive devices for the people with disabilities. As a sensor, TENG has the advantages of zero power consumption, easy manufacturing, lightweight, low cost, etc. It can greatly reduce the threshold for the people with disabilities to use modern electronic equipment and personal monitoring products, and make the use of assistive devices for the people with disabilities including human–computer interaction more convenient. Although the direct application of TENG in the field of assistive devices for the people with disabilities is currently insufficient for TENG, we expect that significant progress will be made in this field in the near future. For example, TENG's structural design and material innovation will be used to expand the range of applications for disabled assistive devices, as well as the industrialization and commercialization of TENG based sensors to make them more suitable for practical applications. Although TENG has enjoyed rapid development in recent years, as an emerging technology, more extensive and in-depth research into TENG is needed to meet the needs of more extensive applications and the requirements of daily use for the people with disabilities, which are summarized as follows:

4.1. Stability and durability of devices

Since TENG is mostly made of polymer and metal materials, the friction layer will be consumed during contact, separation or sliding, reducing its stability and durability. To solve these problems, further improvements in materials are required, or give full play to the advantages of the encapsulation layer. For example, replacing rigid materials with flexible ones such as functional hydrogel, conductive polymer, ionic conductor and so on will reduce the loss of the device and increase their service life. At the same time, if the whole device is made flexible and stretchable, its comfort can be greatly enhanced. Appropriate packaging can not only effectively protect the device, make it dustproof and waterproof, increase its compression resistance, but also optimize the output performance of the device. These research directions being studied may become a breakthrough point in the development of stability and durability of TENG based devices. Stable devices are of great significance to the people with disabilities, which can reduce the number of equipment changes and avoid unnecessary trouble.

4.2. Miniaturization of devices

With the development and maturity of semiconductor technology, the size of electronics has become small enough. However, in comparison, the current size of TENG is still too large in the research stage of the laboratory due to handmade. So that the miniaturization of TENG is also necessary to meet the needs of small-scale applications. To solve this problem, industrial processing and manufacturing technologies are very necessary, which will be more delicate than manual, and can effectively reduce the size of the device, and ensure the uniform performance of the device. While reducing the size of the device, the high output performance of devices still be needed, which depends on the development of new materials science, reasonable structures, and advanced manufacturing technologies. For example, more advanced micromachining technology can be used to further study on the impact of various microstructures (shape, arrangement, size, etc) on the output performance. In addition, device array is also the future trend to realize the diversification of functions. Smaller devices, better output performance and diversified functions can make it more widely used in assistive tools for the people with disabilities. Such as prosthetic pressure detection, fingertip tactile sensation, etc.

4.3. Optimization of devices

Although the current TENG has the advantages of high voltage output and high sensitivity as a sensor, there are still some problems in the process of using. For example, when it is used as a wearable sensor, complex human activities will cause great signal interference; the output performance of TENG can be significantly affected in humid, low, or high temperature environments, and these problems still need to be addressed through further optimization. Therefore, it is particularly important to study the packaging materials that are moisture-proof, corrosion-proof and temperature-insensitive. In addition, some algorithms can be used to filter out unwanted clutter, to detect the living state and rehabilitation state of the people with disabilities more accurately.

4.4. Integration of systems

Not only the optimum design of TENG needs to be perfected, but also the overall system composition. TENG is mainly used as energy or sensors at present, just as a display of the application. Current research often transfers the collected information to the computer for processing and analysis, which dramatically reduces the advantage that these devices can be carried freely, this is far from enough as a practical application. Taking human–computer interaction as an example, the system architecture, data acquisition circuit, signal processing algorithm, and security protocol all need to be deeply customized. Most of the systems are large and lack of high integration, so they need to be highly integrated and miniaturized. Real-time on-site acquisition and analysis are the important directions for the development of TENG based devices. In addition, the compatibility of TENG as a sensor element should also be considered for use in various systems.

4.5. Portable and implantable

The unique advantages of TENG make it suitable for the field of health care, including biomedical applications on the body surface and in the body, to perform physiological signal detection and play an auxiliary role in organs. Therefore, TENG-based biosensors or systems should be portable and implantable. The high integration of functions makes such devices portable. For implantable TENG, although devices with good short-term biocompatibility have been developed, the long-term biosafety needs to be further evaluated. In addition, the effective fixation of the device on the skin, organs and tissues is also important.

The modification of surface structure and tissue adhesives can solve this problem, but more effective approaches still need to be studied. The continuous innovation of principle, materials and means of integration make the functions of these devices richer and more practical for clinical diagnosis and monitoring. This is of great significance to the rehabilitation of the people with disabilities.

With the development of materials science, structural mechanics, and engineering technology, TENG-based assistive devices for the people with disabilities will attract more and more researchers to innovate and improve, which will promote the development of disability and bring more convenience to the people with disabilities. In the future, TENG-based assistive devices for the people with disabilities will be highly integrated, with richer functions and broader application scenarios. It will not only develop rapidly in the field of wearables, but also have a good development prospect in large devices such as wheelchair, intelligent prosthetic limb, and interactive display screen, and so on. Hope to bring convenience to more types of disabled people.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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