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Cutting-edge Piezo/Triboelectric-based Wearable Physical Sensor Platforms

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Abstract

With the recent widespread implementation of Internet of Things (IoT) technology driven by Industry 4.0, self-powered sensors for wearable and implantable systems are increasingly gaining attention. Piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs), which convert biomechanical energy into electrical energy, can be considered as efficient self-powered sensor platforms. These are energy harvesters that are used as low-power energy sources. However, they can also be used as sensors when an output signal is used to sense any mechanical stimuli. For sensors, collecting high-quality data is important. However, the accuracy of sensing for practical applications is equally important. This paper provides a brief review of the performance advanced by the materials and structures of the latest PENG/TENG-based wearable sensors and intelligent applications applied using artificial intelligence (AI).

Keywords: PENG/TENG-based wearable sensors, Self-powered sensors, Artificial intelligence, Intelligent sensor

1. INTRODUCTION

In the Fourth Industrial Revolution, artificial intelligence (AI), the Internet of Things (IoT), and big data industries are rapidly emerging. Sensors are essential tools in these industries. A sensor is a device that converts a physical quantity into an electrical signal or data. Recently, research has been conducted on self-powered sensors that incorporate eco-friendly energy-conversion technology without external power requirements [1]. Piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs) are representative technologies that convert mechanical energy into electrical energy. PENGs take advantage of the direct piezoelectric effect, which occurs when the structural deformation of a piezoelectric material caused by applied pressure generates a potential difference due to a change in electrical polarization. PENGs can be used as implantable sensors or as sensors for building structure diagnosis because they allow accurate control. TENGs generate electrical energy based on triboelectrification and electrostatic induction caused by surface-to-surface contact. Because TENGs are lightweight, flexible, and affordable, research on their use in wearable sensors has been conducted [2].

Lightness, flexibility, and stable signal output are essential for the real-life application of wearable sensors. Recently, the synthesis of various materials and structural designs has been widely studied to improve the performance of wearable sensors [3, 4]. The performance of PENGs has been enhanced through organic and inorganic composite material fabrication, nanostructure fabrication, and 3D structural design. The performance of TENGs has also been continuously improved through the selection of triboelectric materials, considering electron affinity and work function, surface modification through the application of micro/nano patterns, and chemical functionalization of the surface [5]. In addition to these methods, hybridization with other technologies, such as electrode design fabrication and charge injection has been conducted. The performance of a PENG-based sensor depends on the direction of the polarization and electrode connection. In contrast, the performance of a TENG-based sensor depends on the operation modes and structures, such as core-shell, arch, and circle. Although it is possible to fabricate high-performance sensors using nanocomposite materials with proper structural design, nanocomposites with excellent ductility and elasticity present disadvantages in their complex and expensive manufacturing processes.

In addition, there is a limit to the accurate identification of

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multiple signals in a sensor array. This is because research thus far has mainly focused on signal analysis of the data measured by the sensor. PENGs limit the accurate localization of signals because of the reaction between adjacent units in the event of stress. In addition, electrostatic induction in TENGs generates crosstalk between the electrode and sensor unit. A study on correcting sensor signals using machine-learning algorithms and securing reliable data has been proposed to solve such problems [6]. By applying AI to PENG or TENG-based sensors, many of the limitations mentioned above have been overcome. In this paper, we review the recent progress and future direction of PENG/TENG-based wearable sensor technology, which is the essence of Industry 4.0.

This brief review summarizes the performance of grafting various materials, structures, and AI in recent years, as well as applications based on intelligent PENG/TENG sensors.

2. PENG-based Wearable Sensors

Fig. 1(a) shows a monolayer SnS PENG with enhanced performance, fabricated using the liquid-metal-based synthesis process [7]. Because the 2D monolayer SnS was a single crystal across the plane, an enhanced piezoelectric coefficient was achieved. Through direct surface-reaction-based synthesis, the production of large-area monolayer tin compounds that enable the fabrication of sensors with excellent performance was achieved. Fig. 1(b) shows the BTS-GFF/PVDF composite piezoelectric film-based sensor fabricated by the continuous deposition of piezoelectric $BaTi_{0.88}Sn_{0.12}O_3$ (BTS) film on flexible glass fiber fabrics (GFF) [8]. The surface of the BTS-GFF composite was covered with a layer of poly(vinylidene fluoride) (PVDF) film, which improves the composite film because it is more flexible and sturdier. Owing to the high piezoelectric coefficients of BTS, small changes in the force can induce large changes in polarization. The sensor exhibited a voltage sensitivity of 1.23 V N^{-1} and a current sensitivity of 41 nA N^{-1}. This performance is superior to that of previously reported BZT-BCT/P(VDF-TrFE)-based piezoelectric sensors [9]. Fig. 1(c) shows a PENG with a rational 3D structure fabricated by samarium/titanium co-doping on $BiFeO_3$ (BFO) [10]. The 3D porous structure enhanced the stress-transmitting capacity of the interconnected piezoelectric fillers, which resulted in an output performance five times better compared with that of undoped PENG without a 3D porous structure. In addition to the performance enhancement of PENG through the modification of piezoelectric materials, its performance can also be enhanced by controlling the morphology of the PENG structure. One-dimensional fiber-based PENG was fabricated in the form of a fabric through a weaving process for high electrical energy output. A hybrid piezoelectric fiber can be produced by

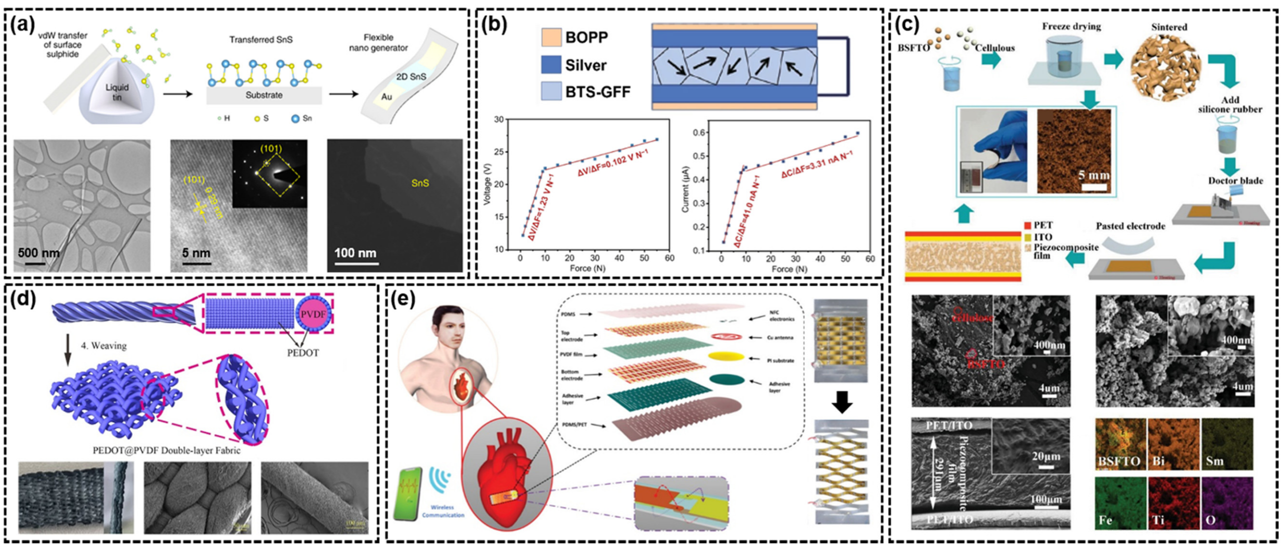

Fig. 1. PENG-based wearable sensor for materials and structures. (a) Synthesis process of monolayer SnS PENG. Reprinted with permission from Ref. [7]. Copyright (2020) Springer Nature. (b) BTS-GFF/PVDF sensor and voltage/current sensitivity. Reprinted with permission from Ref. [8]. Copyright (2021) Springer Nature Switzerland AG. (c) Fabrication process of the PENGs based on the interconnected 3D porous structure. Reprinted with permission from Ref. [10]. Copyright (2019) John Wiley and Sons. (d) Preparation of PEDOT@PVDF nanofiber woven fabric and SEM images of BSFTO. Reprinted with permission from Ref. [13]. Copyright (2017) Springer Nature. (e) Stretchable self-powered sensing systems with wireless communication interface. Reprinted with permission from Ref. [14]. Copyright (2019) John Wiley and Sons.

melt spinning using barium titanate (BT) nanoparticles and polyvinylidene fluoride (PVDF) [11]. The PENG fabric, made up of 98% β-phase hybrid PVDF/BT_{10} piezoelectric fibers had a power density of 87 μm cm^{-3} (labeled PVDF/BT_{10}, where 10 is the wt % of BT in the PVDF polymer). It was six times faster than the previously reported PVDF-film-based PENG [12] at charging a 10 μF capacitor. Fig. 1(d) shows a pressure-sensitive nanofiber-woven fabric sensor fabricated by weaving a poly(3,4-ethylenedioxythiophene) (PEDOT)-coated PVDF nanofiber yarn [13]. The multilevel hierarchical structure of the pressure sensor yielded high sensitivity (18.4 kPa^{-1} at ~100 Pa) and fast response (15 ms). Multilevel dome arrays from the micro/nano scale in the pressure sensor can contribute to various contact joints and a considerable variation in the contact area for pressure sensing. In addition to fabric PENG technologies, as shown in Fig. 1(e), introducing the Kirigami sructure to the PENG geometry improved the stretchability of the PENG strain sensor while maintaining mechanical integrity [14]. The power output and strain sensitivity could be improved by applying intersegmented electrodes. The output voltage (18.4 V) of the Kirigami structure with intersegment electrodes was higher than that of a continuous electrode structure (0.19 V). The output power was 228 W. Compared with previously reported methods for enhancing sensor device stretchability, this design can facilitate the microfabrication process owing to its simple processing technique.

3. TENG-based Wearable Sensors

Recently, new functional materials have been developed for use in TENG-based sensors. Fig. 2(a) shows an ionic liquid-based bionic TENG sensor [15]. Unlike previously reported methods that use energy from ion-concentration gradients, this sensor mimics the structure of ion channels in the electric cell membranes of electric eels. It forms a polydimethylsiloxane (PDMS) -silicone double-layer structure and utilizes the stress mismatch effect between the two materials. This allows underwater sensing or sensing in humid environments through two types of working mechanisms. In single-electrode mode, the peak power density can reach 18 mW m^{-2}, whereas it can reach 62.5 μW m^{-2} in liquid-

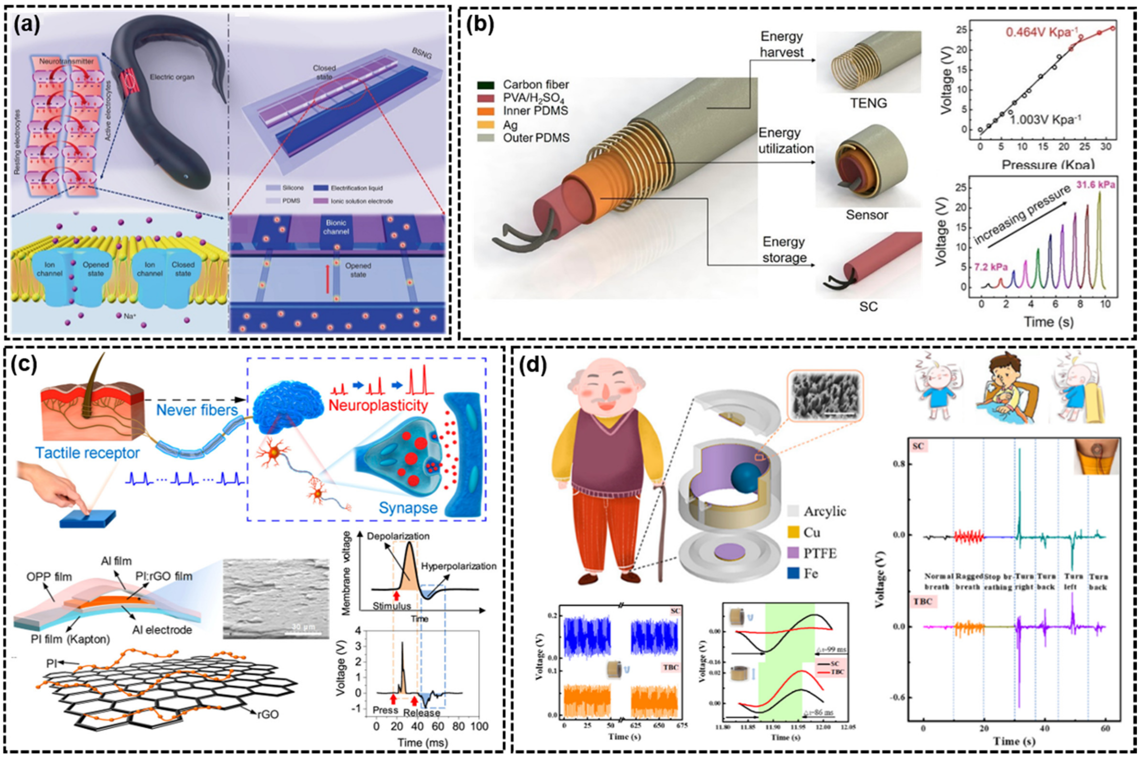

Fig. 2. TENG-based wearable sensor for materials and structures. (a) Structure and principle of bionic stretchable nanogenerator. Reprinted with permission from Ref. [15]. Copyright (2019) Springer Nature. (b) Multifunctional coaxial energy fiber and force-voltage curve. Reprinted with permission from Ref. [17]. Copyright (2021) American Chemical Society. (c) Intelligent neuromorphic sensor and recorded tactile information. Reprinted with permission from Ref. [18]. Copyright (2019) American Chemical Society. (d) A smart wearable sensor and SEM image of the PTFE film. The response time of the V_{OC} and sleep state monitoring. Reprinted with permission from Ref. [19]. Copyright (2021) MDPI.

solid contact mode. The TENG was optimized using a polyvinyl alcohol (PVA) -gelatin composite film [16]. In PVA blends, intramolecular proton transfer between the carboxylic and amine groups leads to +/- charge separation in gelatin. These charges can increase the ionic polarization in the PVA-gelatin system. Therefore, both interfacial and ionic polarizations can be engineered to modulate the dielectric properties of triboelectric materials. The films were optimized for high mechanical deformation and biocompatibility, and exhibited stable and improved triboelectric outputs.

Hence, single-fiber-based TENGs are widely used for wearable sensors and energy harvesting applications owing to their simple structure and free form factor. Fig. 2(b) shows a multifunctional coaxial energy fiber comprising a TENG, supercapacitor (SC), and pressure sensor [17]. It is implemented as a core-shell architecture to incorporate multiple functions. The pressure sensors demonstrated a sensitivity of 1.003 V kPa^{-1} for the real-time monitoring of finger movements below 23 kPa. Fig. 2(c) shows a TENG tactile sensor that mimics the neuromorphic functions of synaptic reinforcement and memory [18]. Is was designed with an arcuate structure to sustain a longer separation process than the contact process. The press-release cycle generates a voltage signal with a positive component, followed by a negative component (Fig. 2(c), bottom graph). The results reveal that the voltage waveform is similar to that of the biological action potential (Fig. 2(c), top graph). Intelligent neuromorphism can actively generate signals of various amplitudes according to external pressure. Fig. 2(d) shows a dual-channeled TENG-based smart wearable sensor

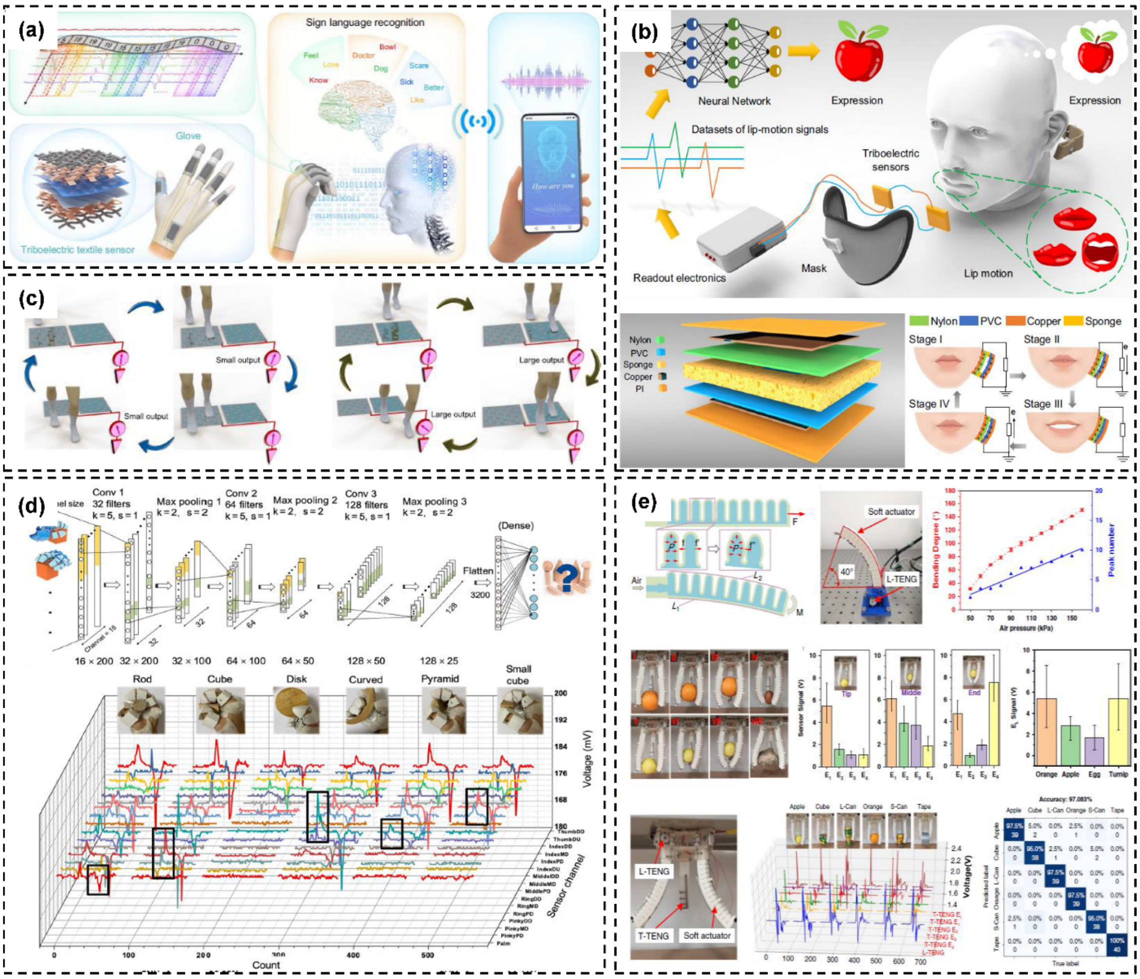

Fig. 3. Deep learning-based applications. (a) Sign language recognition system integrating TENG based sensors to read sentences. Reprinted with permission from Ref. [20]. Copyright (2021) Springer Nature. (b) Flexible TENG based sensors for the recognition of language from lip movement. Reprinted with permission from Ref. [21]. Copyright (2022) Springer Nature. (c) An intelligent floor monitoring system with triboelectric sensor arrays. Reprinted with permission from Ref. [22]. Copyright (2020) Springer Nature. (d) TENG-based sensors and piezoelectric simulators for sensing multidirectional motions. Reprinted with permission from Ref. [23]. Copyright (2020) AAAS. (e) Patterned-electrode tactile TENG (T-TENG) for identifying specific objects through motion change. Reprinted with permission from Ref. [24]. Copyright (2020) Springer Nature.

[19]. This sensor is made in the shape of a ring and can be worn on a finger or attached to a textile to satisfy various requirements. Because it is a dual-channel design, it can sense different modes depending on where it is worn. This simple fabrication process, composed of PTFE and Fe, is advantageous for mechanized mass production.

4. AI Application in Wearable Sensors

Fig. 3(a) shows a sign language recognition glove, integrated with TENG-based sensors, that comprehends sentences by distinguishing different haptic motions using a deep-learning model. It performs with an accuracy of 86.67% in recognizing new/never-seen sentences [20]. Fig. 3(b) shows a lip-language decoding system (LLDS) with flexible TENG-based sensors that uses deep-learning analysis [21]. Lip muscle motion is converted to electrical signals using a flexible sensor, which are then identified using a trained neural network. The sensor was fabricated by stacking polyvinyl chloride (PVC) and polyamide films on both sides of a sponge, followed by attaching a copper film on the top side. An arrayed triboelectric sensor was introduced in deep learning-enabled smart mats (DLES-mats) for intelligent floor monitoring, as shown in Fig. 3(c) [22]. The distinct patterns of step position identify a person's footsteps with high prediction accuracy (96%); thus, the system promises great potential in healthcare, security, and IoT. As shown in Fig. 3(d), an AI-based triboelectric smart glove has been developed to observe multidirectional motion via a deep learning mechanism for human-machine interfaces (HMIs) [23]. The system is combined with TENG-based sensors and a piezoelectric haptic simulator. The authors also demonstrated haptic simulation using a smart glove for virtual reality (VR) training. Fig. 3(e) illustrates a patterned-electrode tactile TENG (T-TENG) sensor for monitoring contact position, gripping pressure, and sliding. Object identification is achieved by applying machine learning to the perceived real-time motion changes from the sensor [24].

5. CONCLUSION

We reviewed the development status of PENG/TENG-based wearable and intelligent sensors combined with AI. Research on performance improvement has been broadly divided into material and structural developments. Despite rapid progress in material synthesis, porosity, weaving, geometric structure, bioengineering, neuromorphic, etc., there is a limit to satisfying both the accuracy and reliability of the sensor. The performance can be improved by signal correction using machine learning algorithms. Until now, the applicability of these sensors has been validated only in various preceding studies. However, the development of intelligent sensors based on innovative materials and structures would be a step toward commercialization.

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