Wearable and Implantable Triboelectric Nanogenerators

Zhuo Liu, Hu Li, Bojing Shi, Yubo Fan, Zhong Lin Wang,* and Zhou Li**

Triboelectric nanogenerators (TENGs) are a promising technology to convert mechanical energy to electrical energy based on coupled triboelectrification and electrostatic induction. With the rapid development of functional materials and manufacturing techniques, wearable and implantable TENGs have evolved into playing important roles in clinic and daily life from in vitro to in vivo. These flexible and light membrane-like devices have the potential to be a new power supply or sensor element, to meet the special requirements for portable electronics, promoting innovation in electronic devices. In this review, the recent advances in wearable and implantable TENGs as sustainable power sources or self-powered sensors are reviewed. In addition, the remaining challenges and future possible improvements of wearable and implantable TENG-based self-powered systems are discussed.

1. Introduction

In the past ten years, the synergistic development of advanced materials/electronics and manufacturing promoted progress in the electronic industry.[1] Portable electronics with wearability[2] and multifunctionality[3] are becoming increasingly attractive to the public. Practical portable electronics require small electronic components and integration ability with cloth fabrics and accessories such as watches, eyeglasses, shoes, bracelets, or in vivo implants[4] in the human body for healthcare monitoring and clinical therapy.[5] However, most current practical portable electronics need power sources to provide electricity to function.[6] The periodic replacement of these power sources commonly causes environmental concerns,[7] poor user experience,[8] heavy financial burden and physical pains to patients.[9] Therefore, it is critical to realize the self-powered operation of practical portable electronics to add convenience to daily life and health supervision.

In 2012, Wang et al. proposed the triboelectric nanogenerator (TENG) as an energy harvesting technology.[10] The basic working mechanism of TENGs comprises the coupling of triboelectrification and electrostatic induction during the conversion of mechanical energy to electricity. The TENG has many advantages including low cost, structural diversity,[11] stable electric output,[12] high energy conversion efficiency,[13] shape-adaptive ability[14] and ecofriendly features.[15] Recently, the TENGs have been made to harvest mechanical energy from environment, such as water wave,[16] vibration,[17] raindrop,[18] and wind.[19] What's more notable is that the unique working mode also allows for applications of TENGs in sportive and physiological situations to harvest biomechanical energy, including body movement,[20] breathing,[21] and heart beating.[22] The electric energy converted by the TENGs can be used for enhancing neural differentiation of mesenchymal stem cells[23] and promoting osteoblasts' proliferation and differentiation[24] in the field of tissue engineering.

To meet the practical operation requirements for self-powered portable electronics, various wearable and implantable TENGs are designed to harvest relevant biomechanical energy,[25] where the wearable TENGs functions outside of bodies, and the implantable TENGs have the capability of operating in vivo.[26] The advantages of the TENG have led to rapid development of wearable and implantable TENGs with the joint efforts of researchers, especially in practical portable electronics.[27] The electricity converted by these TENGs can power low-energy electronics such as watches, calculators, and LED arrays.[28] In addition, physiological information of body can be obtained from the electrical signals generated by wearable and implantable TENGs, including heart rate,[22] pulse,[29] cardiac arrhythmias, and respiratory rates.[30] Therefore, wearable and implantable TENGs can be utilized as a stabilized power source for practical portable electronics and as an active sensor. Nevertheless, if the wearable and implantable TENGs are truly applied to clinical practice and daily life, it will also face challenges in vitro and in vivo, such as efficient energy management, biosafety, biocompatibility, longevity of service, biodegradability, miniaturization, and integration.

Z. Liu, H. Li, Dr. B. Shi, Prof. Y. Fan
Beijing Advanced Innovation Centre for Biomedical Engineering
Key Laboratory for Biomechanics and Mechanobiology of Chinese Education Ministry
School of Biological Science and Medical Engineering
Beihang University
Beijing 10083, China
E-mail: yubofan@buaa.edu.cn

Prof. Z. L. Wang, Prof. Z. Li
CAS Center for Excellence in Nanoscience
Beijing Key Laboratory of Micro-Nano Energy and Sensor
Beijing Institute of Nanoenergy and Nanosystems
Chinese Academy of Sciences
Beijing 100083, China
E-mail: zhong.wang@mse.gatech.edu; zli@binn.cas.cn

Prof. Z. L. Wang, Prof. Z. Li
School of Nanoscience and Technology
University of Chinese Academy of Sciences
Beijing 100049, China

Prof. Z. L. Wang
School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta, GA 30332, USA

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In this review, we first describe the recent advances on wearable and implantable TENGs as sustainable power sources or self-powered sensors. **Figure 1** shows the frame of this article. In addition, we discuss the remaining challenges of wearable and implantable TENGs and TENGs-based self-powered system. Finally, we suggest the new research directions to alleviate them. This review could promote the future evolution of portable electronics in daily life and in clinic.

2. Fundamentals of TENGs

The triboelectric effect is often regarded as annoying or even hazardous in daily life because it may give rise to ignition, dust absorption and damage to electronics.[31] In comparison, the energy harvesting of a TENG from its surroundings relies on the coupling effects of triboelectrification and electrostatic induction.[10] Therefore, factors influencing these two physical processes impact the electric output performance of a TENG, especially the materials' intrinsic properties such as the electron affinity, work function and friction.

Researchers have studied the polarity of friction materials based on their ability to gain electrons (electronegativity) or lose electrons (electropositivity) upon contact with other materials and defined it as the "triboelectric series," which can be used as guidance for selection of materials in TENG fabrication (**Figure 2**a).[32] The greater the variation in the triboelectric series, the more transferred charge between the friction materials. In addition, according to the configuration structure and driving manner, four working modes of TENGs have been proposed to achieve the collection for different forms of mechanical energy, including vertical contact–separation mode,[33] lateral sliding mode,[34] single-electrode mode,[35] and free-standing triboelectric-layer mode[17b,36] (Figure 2b).

3. Wearable TENGs

Wearable electronic devices can be directly worn on body or integrated into user's clothing and its accessories. They not only exist as hardware equipment, but also rely on software support and data interaction to realize their specific functions. Recently, TENGs have become wearable and smart as energy power supplies and sensors on different body positions. According to the independent degree to realize the specific function, the wearable TENGs can be clarified into two types: i) directly wearable TENGs as independent work unit; ii) indirectly TENGs integrated with cloth fabrics, shoes, and other accessories.

3.1. Directly Wearable TENGs

3.1.1. As Active Sensors

On ears, TENG application scenario on ears was demonstrated by Guo et al.[37] This directly wearable TENG adopted the vertical contact–separation working mode (**Figure 3**a). Based on flexible materials and smart structures, the researchers designed a wearable TENG-based self-powered triboelectric auditory sensor (TAS) with advantages of a circular type, easy fabrication and single-channel design. The acrylic, Kapton, Au, a fluorinated ethylene propylene (FEP), and a gap-creating spacer were utilized to assemble the circular device. A nanostructure on the FEP surface was created to realize a higher surface charge to enhance the sensitivity of the TAS. A TAS with ultrahigh sensitivity of ≈110 mV dB^{-1} was obtained and showed a large frequency range (100–5000 Hz) based on the

Yubo Fan is the Director of National Research Centre for Rehabilitation Technical Aids of China, Director of the Affiliated Hospital of NRRA. Director of Beijing Advanced Innovation Centre for Biomedical Engineering, Professor and Director of Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education of Beihang University. Prof. Fan specializes in Biomechanics, Mechanobiology, Biomaterials, and Rehabilitation Engineering.

Zhong Lin Wang is the Hightower Chair in Materials Science and Engineering and Regents' Professor at Georgia Tech, the Chief Scientist and Director of the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His discovery and breakthroughs in developing nanogenerators and self-powered nanosystems establish the principle and technological roadmap for harvesting mechanical energy from environmental and biological systems for powering personal electronics and future sensor networks. He coined and pioneered the field of piezotronics and piezophototronics.

Zhou Li is a Professor in Beijing Institute of Nanoenergy and Nanosystems and University of Chinese Academy of Sciences. His research focused on the self-powered medical system, implantable energy harvesting devices and single cell mechanics, including nanobiosensors.

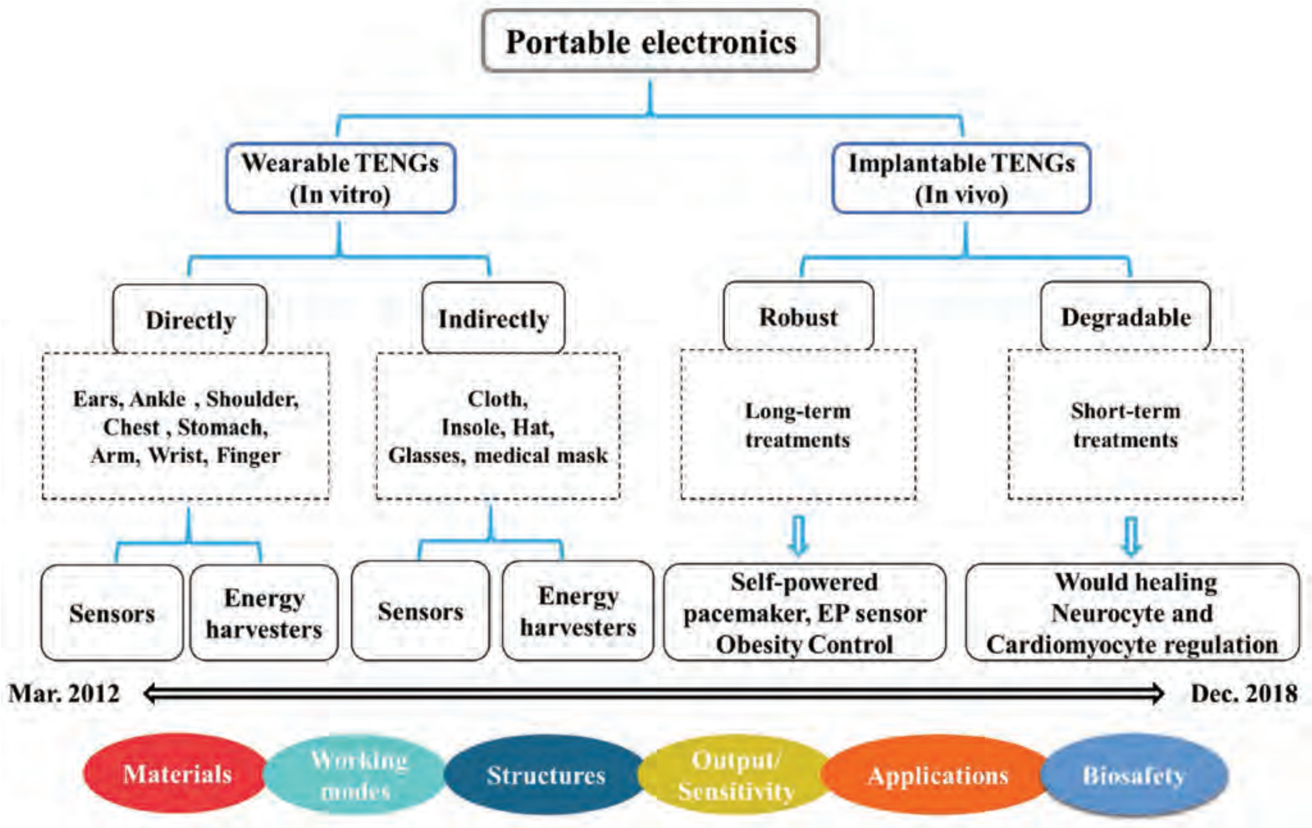
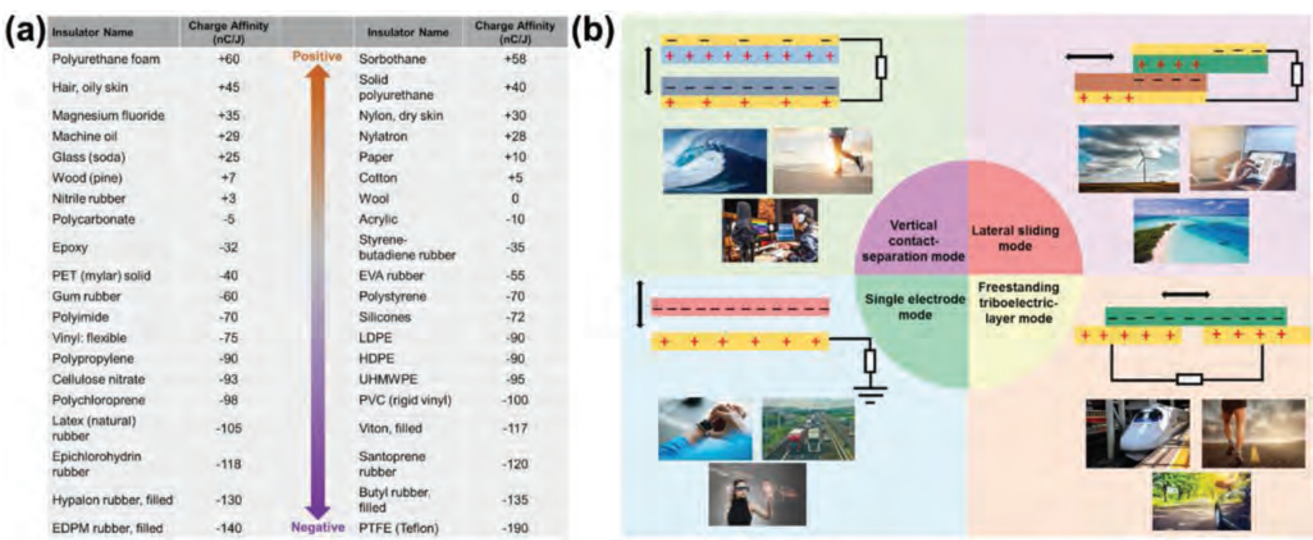


Figure 1. The frame of this article.

newly developed TENG method. This device can be placed directly on the ears for social robotics and hearing aids.

On the neck and other positions, Yang at al. produced the self-powered bionic membrane sensor (BMS) with the same working modes based on the coupling of the contact electrification effect (Figure 3b).[38] The TENG-based BMS work with the vertical contact–separation mode. Nylon, polyethylene terephthalate (PET), indium tin oxide (ITO), and polytetrafluoroethylene (PTFE) were utilized to design a device with an oval shape. The ITO acted as the electrode layer and the nylon and



Insulator Name	Charge Affinity (nC/J)		Insulator Name	Charge Affinity (nC/J)
Polyurethane foam	+60	Positive	Sorbothane	+58
Hair, oily skin	+45		Solid polyurethane	+40
Magnesium fluoride	+35		Nylon, dry skin	+30
Machine oil	+29		Nylatron	+28
Glass (soda)	+25		Paper	+10
Wood (pine)	+7		Cotton	+5
Nitrile rubber	+3		Wool	0
Polycarbonate	-5		Acrylic	-10
Epoxy	-32		Styrene-butadiene rubber	-35
PET (mylar) solid	-40		EVA rubber	-55
Gum rubber	-60		Polystyrene	-70
Polyimide	-70		Silicones	-72
Vinyl: flexible	-75		LDPE	-90
Polypropylene	-90		HDPE	-90
Cellulose nitrate	-93		UHMWPE	-95
Polychloroprene	-98		PVC (rigid vinyl)	-100
Latex (natural) rubber	-105		Viton, filled	-117
Epichlorohydrin rubber	-118		Santoprene rubber	-120
Hypalon rubber, filled	-130		Butyl rubber, filled	-135
EDPM rubber, filled	-140	Negative	PTFE (Teflon)	-190

Figure 2. Fundamentals of TENGs. a) Triboelectric series of commonly used friction materials based on their ability to lose or gain electrons. Reproduced with permission.[32] Copyright 2017, Elsevier. b) Working modes of TENGs: vertical contact–separation mode, lateral sliding mode, single-electrode mode, freestanding triboelectric-layer mode.

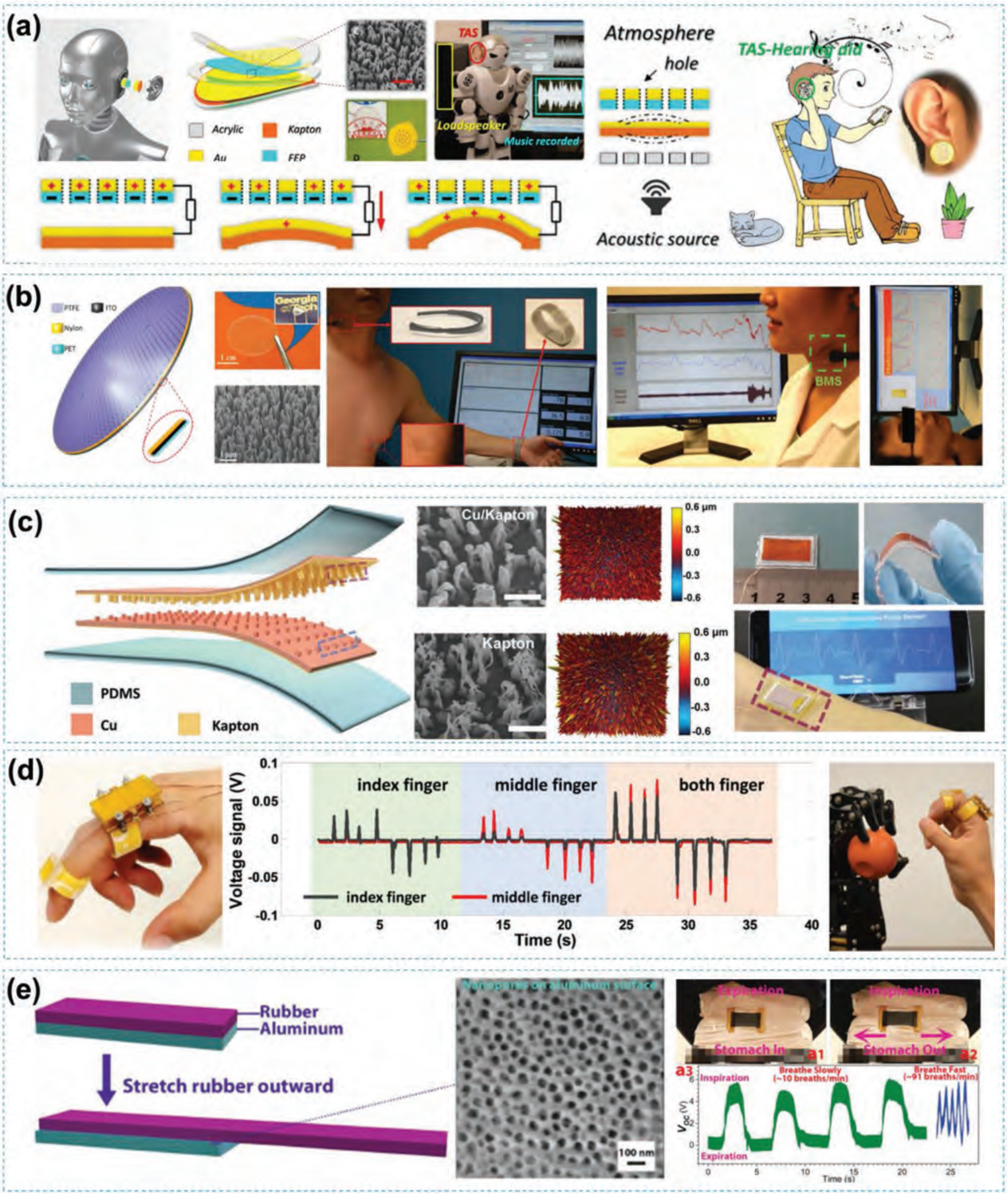


Figure 3. Directly wearable TENGs as active sensors for a) Hearing aids and social robotics on the ears. Reproduced with permission.[37] Copyright 2018, The American Association for the Advancement of Science. b) Monitoring physiological signal on neck and other positions. Reproduced with permission.[38] Copyright 2015, Wiley-VCH. c) Diagnosing cardiovascular disease on wrist. Reproduced with permission.[29] Copyright 2017, Wiley-VCH. d) Controlling gesture on finger. Reproduced with permission.[40] Copyright 2018, Elsevier. e) Monitoring diaphragm breathing on stomach. Reproduced with permission.[41] Copyright 2015, Wiley-VCH.

PTFE were chosen as triboelectrification layers. To mimic the eardrum of a human being, the two ends of PET were tightly attached to PTFE and nylon, and an air spacer between the PTFE and nylon created the conical cavity which resulted in the charge generation and transfer. The surface of the PTFE had nanosurface modification to enhance the output performance. The working principle of BMS can be outlined as follows: The PTFE layer in response to the mechanical vibration that along with the electricity generation by the contact electrification effect. The sensitivity of BMS is ≈51 mV Pa^{-1} with an extremely low response time with detection pressures below 2.5 Pa. Notably, even after 40 000 working cycles, the loading–unloading signal of the BMS remained stable, exhibiting its outstanding durability. The authors demonstrated that the BMS could be used as a self-powered pulse wave sensor to reveal the condition of the cardiovascular system. In addition, the device can be attached on the throat as microphone without external power to pick up and recover the voice. The BMS is eye-catching, wearable, mini, low-cost and self-powered, and has great potential for application in the field of wearable health care and biometric authentication.

On the wrist, Ouyang et al. fabricated a self-powered pulse sensor (SUPS) with high sensitivity based on a wearable TENG (Figure 3c).[29] This TENG-based SUPS work with the vertical contact–separation mode. The triboelectric layers consisted of Kapton and Cu films. The size of the SUPS after encapsulation is 20 mm × 10 mm × 0.1 mm. The output voltage, current, and transferred charge were typically ≈109 V, 2.97 μA, and 7.6 nC, respectively. SUPS on the radial arteria can generate effective output voltage, current and transferred charges of 1.52 V, 5.4 nA, and 1.08 nC, respectively. In this work, SUPS realized a more accurate Poincare plot with the advantage of high linearity of R–R and P–P intervals based on SUPS and ECG, respectively. The electric signals of the radial artery pulse by SUPS can reflect physiological information regarding coronary heart disease, atrial septal absence, and atrial fibrillation. The SUPS was successfully applied to diagnose cardiovascular diseases and antidiastole. In addition, the SUPS was able to integrate with Bluetooth technology. This device also realized the wireless detection of cardiovascular diseases based on the pulse signal. Combined with the Bluetooth technology, the SUPS realized accurate, wireless, and real-time monitoring of physiological information for cardiovascular diseases based on the pulse signal. In the future, this wearable TENG-based SUPS can act as a wearable self-powered sensor for effective diagnosis of cardiovascular disease.

On the fingers, Shi et al. proposed a wearable TENG with free-standing mode as active sensor to monitor finger bending in 2016.[39] The device was made of a flexible PET film, polydimethylsiloxane (PDMS) layer, multiple copper (Cu) electrodes, and deionized (DI) water. The working principle of the sensor can be briefly described as follows: the device was fitted on a finger, and the finger joint faced the water chamber center. When the finger bent to some degree, the bending resulted in different pressure. Pressure-induced water flow in the channel of water chamber. Then, the electric signals can be obtained by multiple Cu electrodes on the bottom of the channel. These results indicated that this wearable TENG-based sensor has a great application potential for complex body movement monitoring with optimized structure design. In 2018, Pu proposed a joint motion triboelectric quantization sensor (jmTQS) based on a finger-wearable TENG with advantage of ultrahigh sensitivity to detect the finger joint's flexion-extension degree, speed and direction (Figure 3d).[40] Through correlation calculation, this system can control robotic hand via human gesture. This work contributes to propelling the natural, high-precision and real-time interface.

On the stomach, Yi et al. proposed a stretchable rubber-based TENG with the sliding mode, which can act as an active sensor (Figure 3e).[41] A layer of aluminum film and a layer elastic rubber were used for the device. The charge density and distribution on the surface of the rubber can be changed by releasing and stretching. The device was attached on a human body to detect joint moment and diaphragm breathing.

3.1.2. As Power Sources

Yi et al. developed a stretchable self-charging power system (SSCPS) based on a wearable TENG with vertical contact–separation mode and supercapacitors (**Figure 4**a).[42] The wearable TENG can convert diverse motions into electricity, which was stored in supercapacitors. For the wearable TENG unit, a mixture of carbon black and silicone rubber was used as the friction layer and back electrode, and silicon was employed as another friction layer. To enhance the electric output of the wearable TENG, a sandpaper polishing method was utilized to form nano/microstructures on the surfaces of the friction layers. A stretchable 5 mm × 5 mm supercapacitor was made to store the energy generated by the TENG. The authors demonstrated that the SSCPS showed a stable charging performance with or without contact with water, and the charging rate remained near 178 mV min^{-1}, showing its waterproofness. When the SSCPS is pressed with the hand at a frequency of 1.3 Hz for –8 min, a wearable electronic watch can be driven by the SSCPS for ≈16 s. This finding proved that the SSCPS effectively harvests the biomechanical energy from human motions and can power wearable electronics. This work may represent a new route to fabricate wearable TENGs for wearable electronics with high stretchability.

Lai et al. reported an electric eel skin-inspired triboelectric nanogenerator with the advantages of durability and stretchability to power wearable electronics (Figure 4b).[43] This bioinspired TENG has a single electrode mode. Silver (Ag) nanowires were used as the electrode layer due to their good electrical conductivity and stretchability, and Eco-flex 00-10 silicone rubber was utilized for the stretchable frictional layer and encapsulated material. This device has a single electrode structure, and charge transfer occurs when skin contacts the triboelectric layer (Eco-flex 00-10 silicone rubber). The open-circuit voltage and transferred charge density of this device (2.5 × 2.5 cm^2) can reach 70 V and 100 μC m^{-2}, respectively, under 10 N force. This work demonstrated that the device can power a commercial smart watch when worn on the forearm by hand tapping. Increasingly, the devices realize body-conformable e-skin systems with intuitively visual signals based on TENG arrays and LED. These results will promote the development of flexible electronic devices and human-computer

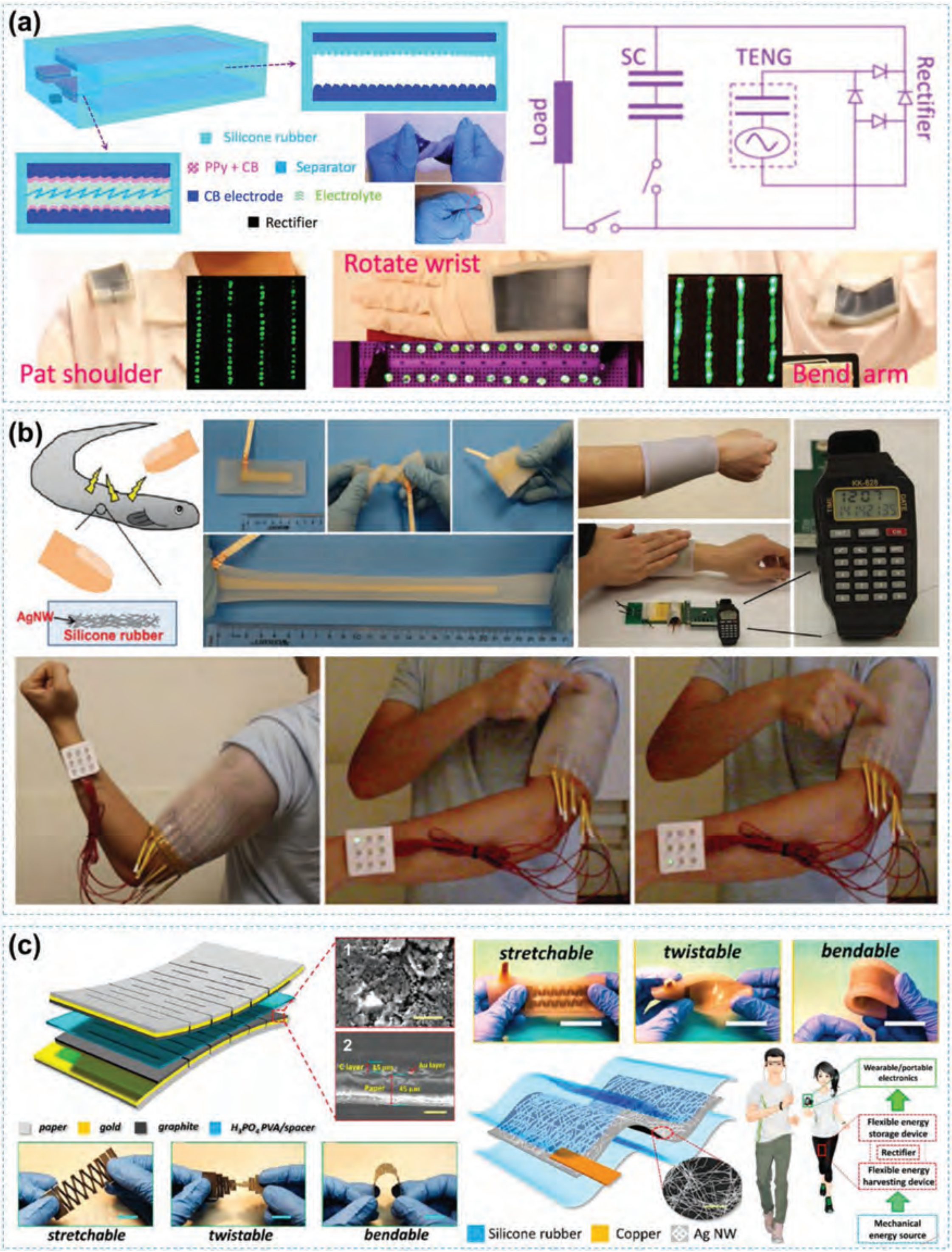


Figure 4. Directly wearable TENGs as power sources with a) Vertical contact–separation mode based on silica rubber and carbon black. Reproduced with permission.[42] Copyright 2016, American Chemical Society. b,c) Single electrode mode based on Ag nanowires and silicon silica gel. b) Reproduced with permission.[43] Copyright 2016, Wiley-VCH. c) Reproduced with permission.[44] Copyright 2016, American Chemical Society.

interaction. In the meantime, Guo et al. developed an all-in-one shape-adaptive self-charging system based on a wearable TENG with same working mode and supercapacitors (Figure 4c).[44] A shape-adaptive silicone rubber and Ag nanowires were utilized to fabricate the stretchable TENG with an output of ≈160 nC and ≈250 V under a 100% stretching state. Paper was chosen to design the supercapacitor with advantages of stretchability and durability. The paper-based supercapacitor was constituted into a TENG with a rectifier that can harvest body motion energy to drive wearable electronics. The authors also demonstrated that the system enables the collection of biomechanical energy to power an electric watch. This work will lead to promising improvements in future self-powered wearable electronics.

3.2. Indirectly Wearable TENGs

3.2.1. As Active Sensors

Indirectly wearable TENGs have adopted vertical contact–separation mode in most cases. Recently, Pu et al. produced a mechnosensational communication system triggered by eye motion based on a TENG with high sensitivity (≈750 mV). The multilayered mechnosensational TENG was mounted on ordinary glass with the single-electrode working mode (**Figure 5**a).[45] The substrate of the mechnosensational TENG was designed using a tadpole-like PET. The electrification layer was made using an FEP, indium tin oxide layer on the PET substrate as the back electrode. Natural latex was utilized as another electrification layer on the top to contact the skin near the eyes. The authors measured the output voltage and corresponding applied pressures at the frequency of 0.5 Hz. With increasing frequency, both the load voltage and the open-circuit voltage increased significantly, meaning that a faster eye blink can lead to a stronger electric signal. Then, the authors designed a smart home control system that consisted of a user, mechnosensational TENG-based smart glass and a signal processing system. To broaden the application scenarios, the ms-TENG was combined with a wireless transceiver module, which realized a hands-free typing system (i.e., typing with eye blinking). With the development of mechnosensational TENGs in different body positions, this device will have various potential applications in future intelligent robotics and for patients with disabilities.

In addition to the intelligent control, the indirectly wearable TENGs can also be integrated with insole and medical mask as an active sensor for monitoring human gait and respiration patterns in real time. Lin et al. developed a TENG based smart insole for monitoring human gait in real time (Figure 5b).[46] The sensor integrated with the conventional insole convert mechanical triggering/impact into electrical signal, including two parts: a TENG part and an elastic air chamber (EAC) part. The TENG part consisted of rubber layer and copper layers to realize the contact–separation. When the mechanical force was released, the EAC part was packaged by latex to accelerate separation between two triboelectric layers with a fast response time of less than 56 ms. These two sensors were placed in the front foot and rear of the insole, respectively. After 1000 cycles, the output voltage of the TENG was about 33 V and maintained stability under the force of 30 N. By analyzing the signal differences of the TENG, gait patterns including jump, step, walk, and run could be accurately monitored. Therefore, the device may also be employed as a fall-down alert system for elder people or patients in the area of health monitoring. In the same year, Wang et al. purposed a self-powered and real-time respiratory sensor based on the TENG embedded in a conventional medical mask (Figure 5c).[47] The device has a simple structure with materials of Cu, nanostructured PTFE, copper wire and acrylic. When the air flow rate increased from 85 to 216 L min^{-1}, the average peak values of output voltage and current increased from 1.7 to 11.1 V and 0.9 to 10.2 µA, respectively. In addition, the authors also investigated the negative effect of humidity on the TENG performance. The electric signals from TENG driven by human breath could be utilized to monitor human respiration patterns in real time. The four different breathing patterns such as slow, rapid, shallow, deep breathing, were recorded though electric signals by the TENG. The low frequency has slower breathing in calm and relaxed situation. Compared to slow frequency, rapid frequency has a faster breathing. Which is strongly reflected the human respiration patterns on the basis of standard pulmonary function test. This work provided a new structure for wearable TENG to achieve health monitoring.

3.2.2. As Power Sources

Integrated with clothes, Seung et al. reported a nanopatterned, flexible and wearable TENG (**Figure 6**a).[48] Ag-coated textile and PDMS were used as triboelectric materials, and the output voltage and current reached 120 V and 65 µA, respectively. The TENG remained stable after 12 000 cycles with excellent mechanical durability. The authors also demonstrated the self-powered operation of light-emitting diodes (LEDs) based on the device without external power sources. This work also provided a feasible energy management strategy for smart clothing using wearable TENGs. Kim et al. developed a stretchable 2D fabric for wearable TENGs (Figure 6b).[49] Aluminum (Al) wires and PDMS tubes serve as the fibers. The output voltage and current of the fabricated wearable TENG reached ≈40 V and 210 µA, respectively. The device can be used in smart clothing applications based on its high robustness, even to 25% stretchability. Pu et al. reported a TENG cloth integrated with an all-solid-state flexible yarn supercapacitor for self-charging power textile (Figure 6c).[50] Straps of Ni-coated polyester and parylene-Ni-coated polyester were employed as longitudes and latitudes to weave the TENG cloth. The A and B electrodes were composed of parylene-Ni-coated and Ni-coated polyester straps, respectively. An open voltage and short circuit of 40 V and 5 µA, respectively, were obtained under at a frequency of 5 Hz. The output performance of the TENG remained almost unchanged with the frequency increase. The reduced graphene oxide (rGO) layer served as an active material. Two rGO-Ni-yarns were connected in parallel as a symmetric yarn supercapacitor, and poly(vinyl alcohol) (PVA)/H_3PO_4 gel was used as a separator and solid electrolyte. The capacitance of the symmetric yarn supercapacitor reached 13.0 and 2.1 mF cm^{-2}. It also achieved a high capacitance retention of ≈96% after 10 000 cycles. This new approach for conductive fabrics and energy storage technology greatly promoted the progress of TENG-based wearable electronics.

Integrated with shoe insole, Zhu et al. developed a self-powered shoe insole using a multilayered wearable TENG with a zigzag structure for consumer electronics (Figure 6d).[51] The TENG consisted of nanoporous aluminum foil, Kapton film, and PTFE film. This TENG device was fully packaged in a shoe insole for energy harvesting from human walking.

Figure 5. Indirectly wearable TENGs as active sensors for a) A mechnosensational communication system, Reproduced with permission.[45] Copyright 2017, The American Association for the Advancement of Science. b) Monitoring human gait. Reproduced with permission.[46] Copyright 2017, Wiley-VCH. c) Monitoring respiration patterns in real time. Reproduced with permission.[47] Copyright 2018, American Chemical Society.

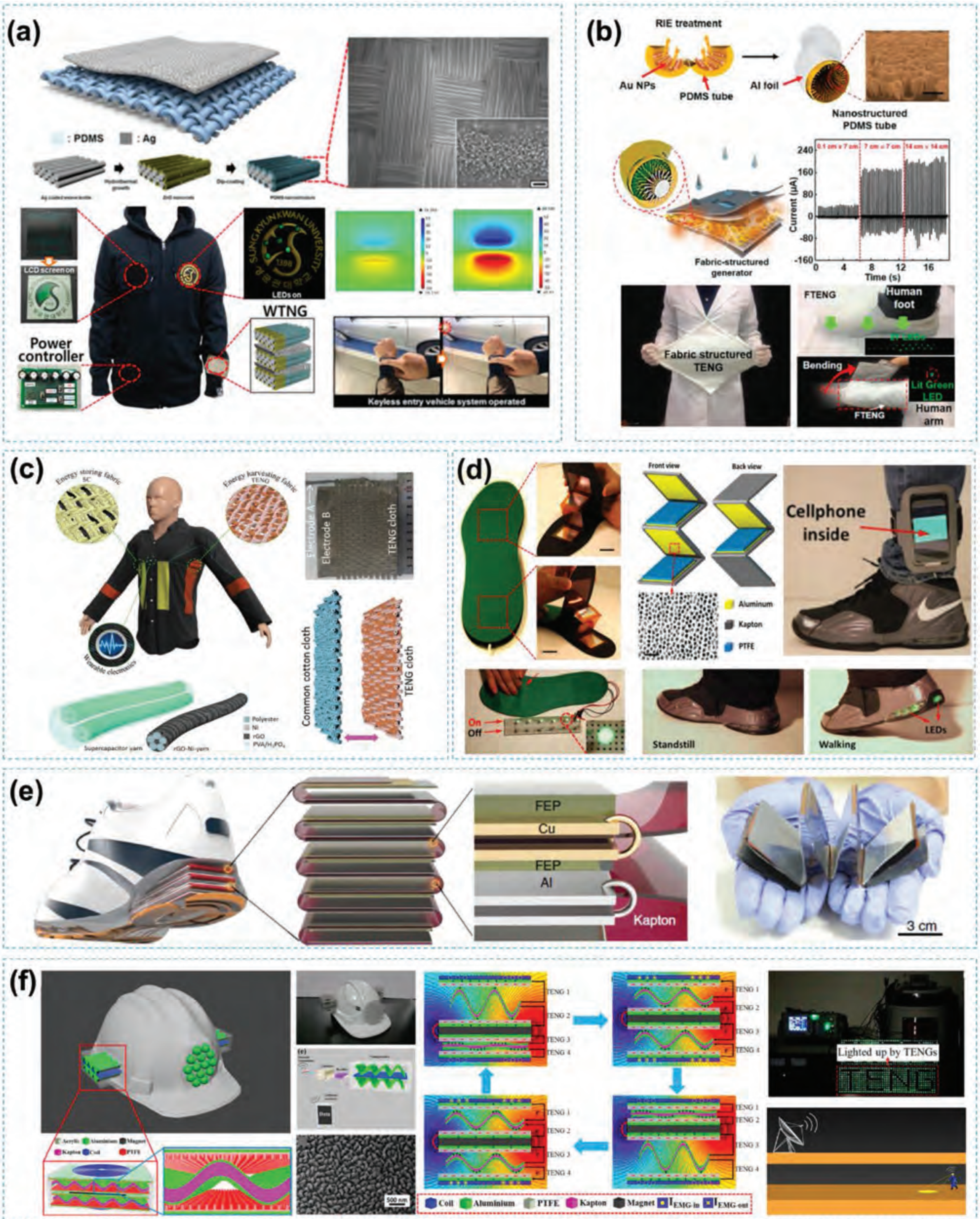


Figure 6. Indirectly wearable TENGs integrated with a–c) cloth fabric. a) Reproduced with permission.[48] Copyright 2015, American Chemical Society. b) Reproduced with permission.[49] Copyright 2015, American Chemical Society. c) Reproduced with permission.[50] Copyright 2016, Wiley-VCH. d,e) Shoes. d) Reproduced with permission.[51] Copyright 2013, Elsevier. e) Reproduced with permission.[52] Copyright 2015, The Nature Publishing Group. f) Hat as a power source. Reproduced with permission.[53] Copyright 2016, American Chemical Society.

Under walking pressure, the developed TENG can produce a high open-circuit voltage of 220 V and a short-circuit current of ≈600 μA. During human walking, the generated electricity can power commercial LED bulbs. In addition, when a person walks with the shoe insole, the insole can serve as a power source to charge a cellphone. The self-charging system was composed of a shoe insole, a cellphone pocket and a plug as connecting line. This work provided a convenient method for energy harvesting and powering of electronic gadgets during normal walking without any limitations of time and place. In 2015, Niu et al. developed a universal self-charging system based on a wearable TENG (Figure 6e).[52] The multilayered contact-mode TENGs had a small volume and light weight ((5.7 × 5.2 × 1.6 cm/29.9 g for a 10-layer TENG and 5.7 × 5.2 × 2.4 cm/43.6 g for a 15-layer TENG)) and were used to effectively harvest biomechanical energy, such as from walking and running. The nanostructure layer was engineered on fluorinated ethylene propylene and Al foil to improve the electric output of the TENG. When the TENG was embedded into shoe insoles, the transferred charge and voltage reached 2.2 μC and 700 V, respectively. In addition, this system can convert AC energy to DC electricity with a high efficiency of 60%. In the demo, when the system was connected to a commercial temperature sensor, ECG system and mechanical sensor, the integrated device functioned normally. This work overcame a shortcoming of self-powered systems, contributing to future wearable TENG-based electronics.

Integrated with helmet, Jin et al. developed a self-powered helmet by hybridizing a wearable TENG and an electromagnetic generator (EMG) for emergency warning (Figure 6f).[53] The commercial helmet adopted a polymer framework with a light weight. The TENG has a multilayered sandwiched structure of wavy Al–Kapton–Al layers and PTFE films. Two coils were placed face-to-face on the top and bottom substrates, and a magnet was anchored in a movable acrylic plate. The variable distance of the magnet and coil induced electric output as an EMG. The TENG and EMG were structurally hybridized on the acrylic as a framework. The hybridized generator was installed on both the sides of a safety helmet to function as the power source to drive the transmitter and LEDs. The generated AC was rectified into DC and stored in a commercial capacitor for light emission and distress signal transmission. The hybridized nanogenerator produced a maximum power density of ≈167.22 W m^{-3}, which was sufficient to power 1000 red commercial LEDs. Furthermore, the converted electricity from human motion can provide energy for a wireless pedometer, which can transmit walking data to a personal mobile. This developed hybridized self-powered helmet can provide sustainable energy for both lighting and positioning. This work created great potential for applications in mine operation, exploration and engineering.

The abovementioned research on wearable TENGs proved the feasibility of using wearable TENGs as energy harvesters to convert biomechanical energy to electricity. After several years of development, the wearable TENGs were fabricated with diverse working modes and increased electric output. The electric output performance of wearable TENGs is increasingly enhanced from 750 mV to 700 V for voltage and 65–600 μA for current. According to their usage and components, the TENGs were clarified and summarized in detail in **Table 1**. The directly wearable TENGs have commonly designed with working modes of vertical contact–separation, freestanding triboelectric-layer, and single electrode. For the indirectly wearable TENGs, the vertical contact–separation is mostly adopted. To meet the specific requirement, the sizes of wearable TENGs can be as small as 0.6 cm × 0.4 cm or as large as 14.0 cm × 14.0 cm. The friction materials are diverse from metals to synthetic/natural polymers and carbon materials. The application scenarios of wearable TENGs covered the healthcare monitoring, smart electronics, and communication system. For most wearable TENGs, the devices have good flexibility and stretchability.

However, the application scenarios of these wearable TENGs were limited in body surface. To achieve in vivo energy harvesting and healthcare monitoring, researchers developed implantable TENGs, which can work in subcutaneous regions, on organ surfaces and in heart chamber (**Figure 7**). In the following section, we overview the fabrication strategy, structure design, electric performance, and application potential of implantable TENGs.

4. Implantable TENGs

Implantable electronic devices can timely monitor the physiological signals or play an assistant role for some organs. With the development of electronic technology, implantable electronic devices are widely accepted by people and used in clinic study. TENG has both sensing and powering functions with advantage of biosafety, which make it suitable for biomedical applications in vivo to realize healthcare monitoring and treatment. According to the operation time in vivo, these TENGs can be clarified as robust implantable TENGs with stable structure and biodegradable implantable TENGs with transient structure.

4.1. Robust Implantable TENGs

A power source with a long life is very important for the safe operation of implantable medical devices such as pacemakers,[54] deep brain stimulators,[55] and medical sensors.[56] Once their batteries are exhausted, these devices need to be replaced, which results in tremendous pain and heavy financial burden to patients.[57] Hence, it is necessary to design robust implantable TENGs as a long-term energy provider. With proper configuration structure design and materials selection, the TENG can also be used for harvesting biomechanical energy and physiological signal sensing in vivo. The feasibility of in vivo implantation were demonstrated successfully in physiological systems of the respiratory, cardiovascular and digestive.

4.1.1. Respiratory System

In 2014, Zheng et al. developed an in vivo self-powered cardiac pacemaker using a breath-driven TENG in SD rats.[58] The TENG device had a small size of 1.2 cm × 1.2 cm × 0.2 cm, with a 0.8 cm × 0.8 cm friction area (**Figure 8**a). The TENG device was implanted beneath the left chest skin in an SD rat (Figure 8b). A PDMS film (100 μm thick) with pyramid arrays

Table 1. The summarization of wearable TENGs.

Type / Futures	Wearable TENGs			
	Directly wearable TENGs		Indirectly wearable TENGs	
	Sensor	Power source	Sensor	Power source
Working modes	Contact–separation,[29,37,38] freestanding triboelectric-layer,[39,40] lateral sliding[41]	Contact–separation,[42] single-electrode,[43,44]	Contact–separation[45–47]	Contact–separation[48–53]
Size [cm^2]	1.5 × 1.5,[37] 0.6 × 0.4,[38] 2.0 × 1.0,[29] ≈2.5 × 7,[39] ≈2.0 × 4.0,[40] 4.0 × 5.0[41]	7.0 × 3.8,[42] 4.5 × 10.5,[43] ≈5.0 × 10.0,[44]	≈2.5 × 2.5,[45] 2.0 × 2.0,[46] 2.0–1.5[47]	≈5.0 × 5.0,[48] 14.0 × 14.0,[49] 10.0 × 10.0,[50] ≈4.0 × 4.0,[51] 5.7 × 5.2,[52] 6.0 × 6.0[53]
Position/accessories	Ears,[37] carotid artery,[29,38] chest,[38] wrist,[29,38] brachial artery,[29] radial artery,[29] finger,[29,39,40] ankle artery,[29] stomach[41]	Shoulder,[42] wrist,[42] arm,[42–44]	Glasses,[45] insole,[46] medical mask[47]	Cloth,[48–50] insole,[51,52] hat[53]
Materials	FEP,[37,40] Au,[37] acrylic,[37,40] Kapton,[29,37] PTFE,[38] ITO,[38] nylon,[38] PET,[38,39] PDMS,[29,39] Cu,[29,39,40] liquid,[39] rubber,[41] Al[41]	Carbon black,[42] silicone rubber,[42–44] AgNW[43,44]	Nature latex,[45] acrylic,[45,47] PET,[45,46] FEP,[45] ITO,[45] Rubber,[46] Cu,[47] PTFE[47]	ZnO nanowires,[48,49] Ag,[48] PDMS,[48,49] cotton,[50] polyester,[50] Au nano particles,[49] Al,[49–52] Ni,[50] Parylene,[50] Kapton,[51,52] PTFE,[51,53] Cu,[52] FEP[53]
Electric output/sensitivity	110 mV dB^{-1},[37] 51 mV Pa^{-1},[38] 1.52 V,[29] 4 nA,[39] 0.5 V[40] ≈6 V[41]	≈400 V (97 μC m^{-2}),[42] 70 V (100 μC m^{-2}),[43] ≈250 V (150 nC)[44]	≈750 mV,[45] 35 V,[46] ≈1.8V[47]	120 V(65 μA),[48] 40 V (210 μA),[49] 40 V,[50] 220 V(600 μA),[51] 700 V (2 μC),[52] 147 V (70 μA)[53]
Biomechanical energy	Sound,[37] pulse,[29,38] finger,[39,40] respiration[41]	Joint,[42] flap [43,44]	Blink,[45] walk,[46] respiration[47]	Body movement,[48–50,53] walk[51,52]
Applications	Hearing aids,[37] monitor arterial pulse wave,[29,38] acquire and recover throatsound,[38] monitor finger motion,[39] human–robot interface,[40] monitor respiration[41]	Drive an electronic watch,[42,44] electronic-skin[43]	Mechnosensational communication system,[45] monitor gait,[46] monitor respiration[47]	Drive wearable electronics[48–53]
Flexibility	Yes,[29,38–40] none[37]	Yes[42–44]	None[45–47]	Yes,[48–52] none[53]
Stretchability	Yes,[41] none[29,37–40]	Yes[42–44]	None[45–47]	Yes,[49] none[48,50–53]

and nanostructured Al foil acted as the friction layers. Kapton and gold (Au) film acted as the supporting substrate and back electrode, respectively. The PET spacer was 400 μm. The inhalation and exhalation of the SD rat caused compression and relaxation of the chest, which made the PDMS film and Al foil contact and separate from each other. The generated output voltage and current reached 3.73 V and 0.14 μA, respectively. The converted electricity powered a cardiac pacemaker for regulation of heartbeats (Figure 8c). Li et al. developed a micro-power supply in vivo based on breath-driven implantable TENG with in-plane sliding mode in 2018. This device can convert slow biomedical motions into continues electric signals with advantages of frequency transforming based on grating electrodes (Figure 8d).[59] A multilayered structure of the device consisted top and bottom Cu/Cr electrode layers (microscale interdigital electrodes (IDEs)), middle layer (mobile layer for electrification) and flexible packaging layer (silicone elastomer, Ecoflex 00-30). PET was utilized as the substrate for IDEs. The whole device has good biocompatibility and flexibility. This device (≈1.5 cm × 3 cm) was implanted inside the abdominal cavity of SD rats, converting the diaphragm movement during normal respiration into a continuous ≈2.2 V direct-current (dc) output though a basic electrical circuit. The LED can be powered by the output of the implantable TENG without attenuation. This improved structure of implantable TENG may promote the development of self-powered biomechanical harvester for driving implantable medical devices.

4.1.2. Cardiovascular System

In clinical therapy, the physiological and pathological signals are necessary for patient monitoring, including heart rhythm, respiratory rate and blood pressure.[60] Life threat and mortality often occur when data on the vital signs of the body are absent. In 2016, Ma et al. developed a self-powered, flexible and one-stop implantable active sensor based on an implantable TENG (3 cm × 2 cm × 1 mm) (Figure 8e).[30] The electric output reached a voltage and current of ≈75 V and 12 μA, respectively. After implanting the TENG in an adult Yorkshire pig, the heart rates, respiratory rates and phases, blood pressure and velocity of blood flow were successfully monitored. The monitoring functionality remained stable for 72 h after closure of the chest. As a multifunctional self-powered biomedical monitor, the proposed TENG holds great application potential in the healthcare industry. Based on the same structure, Zheng et al. fabricated an implantable TENG (6 cm × 4 cm × 1 mm) for self-powered wireless cardiac monitoring in vivo (Figure 8f).[22] Compared with the previous work,[58] the output voltage (14 V) and current (5 μA) of the developed TENG were improved by

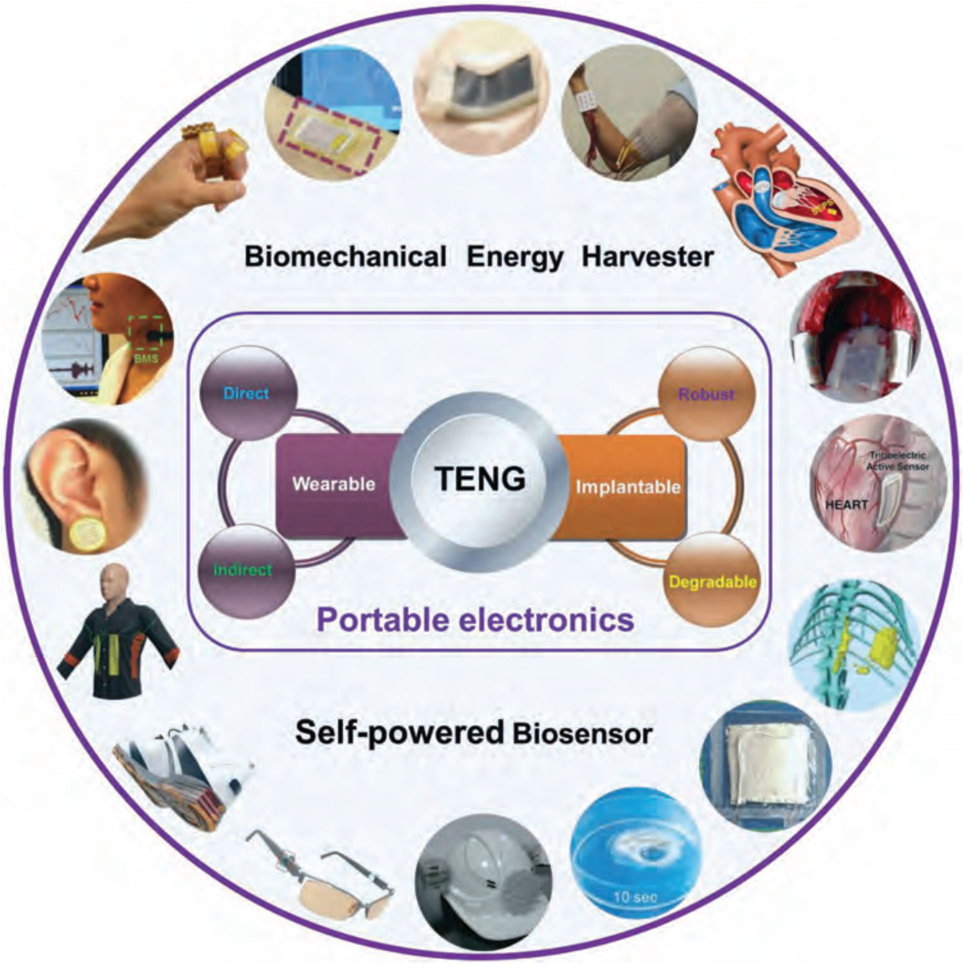


Figure 7. Diverse in vitro and in vivo applications of wearable and implantable TENGs. The figures (clockwise from top): Reproduced with permission.[42] Copyright 2016, American Chemical Society. Reproduced with permission.[43] Copyright 2016, Wiley-VCH. Reproduced with permission.[61] Copyright 2019, Wiley-VCH. Reproduced with permission.[59] Copyright 2018, American Chemical Society. Reproduced with permission.[30] Copyright 2016, American Chemical Society. Reproduced with permission.[69] Copyright 2018, Wiley-VCH. Reproduced with permission.[64] Copyright 2016, The American Association for the Advancement of Science. Reproduced with permission.[65] Copyright 2016, Wiley-VCH. Reproduced with permission.[53] Copyright 2016, American Chemical Society. Reproduced with permission.[45] Copyright 2017, The American Association for the Advancement of Science. Reproduced with permission.[52] Copyright 2015, The Nature Publishing Group. Reproduced with permission.[50] Copyright 2016, Wiley-VCH. Reproduced with permission.[37] Copyright 2018, The American Association for the Advancement of Science. Reproduced with permission.[38] Copyright 2015, Wiley-VCH. Reproduced with permission.[40] Copyright 2018, Elsevier. Reproduced with permission.[29] Copyright 2017, Wiley-VCH.

3.5 and 25 times, respectively. The developed implantable TENG was connected to an implantable wireless transmitter, and the obtained experimental data was transmitted for real-time cardiac monitoring. The real-time heartbeat of an adult Yorkshire porcine was successfully monitored through the wireless transmitted signal. This work demonstrated the great potential of using implantable TENGs for self-powered, wireless healthcare monitoring systems. Compared with large size TENG in vivo, smaller size will broaden the application scenarios, which puts new demands on the sensitivity of the device.

In 2018, Liu et al. proposed a novel technology for monitoring endocardial pressure based on implantable TENG with the size of 1.0 cm × 1.5 cm × 0.1 cm (Figure 8g).[61] In this work, PTFE film as triboelectric layers was treated by inductively coupled plasma (ICP) and corona discharge, which enhanced the output performance of the self-powered endocardial pressure sensor (SEPS) from 1.2 to 6.2 V. Al foil was another triboelectric layer. A flexible PDMS with advantages of biocompatibility and blood compatibility was chosen to encapsulate the device. In a swine model, the SEPS was integrated with a surgical for minimally invasive implantation duo to its microdimension, and implanted into ventricle and atrium. The experiment results showed that the SEPS had good response both in low- and high-pressure environment and achieved excellent linearity (R^2 = 0.997) with a sensitivity of 1.195 mV $mmHg^{-1}$. In addition, the cardiovascular disease, such as ventricular premature contraction and ventricular fibrillation were observed by detecting the EP of a swine. Here, the SEPS realized the implanting position of implantable TENG from subcutaneous region and surface of the heart to cardiac chambers, which expanded the application scenario of the implantable TENG. This work may provide a good idea for self-powered miniature implantable sensor to monitor and prevent the cardiovascular diseases.

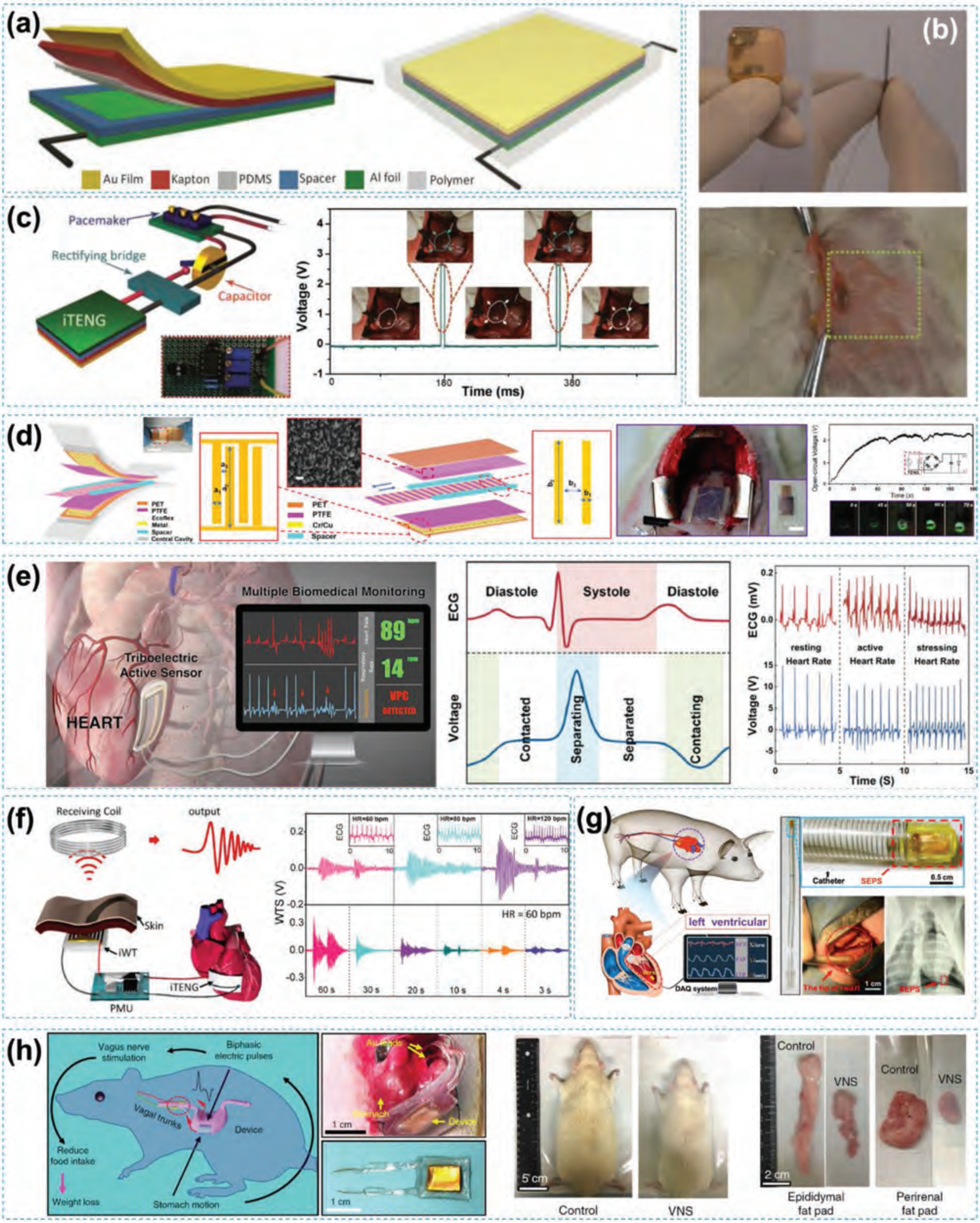


Figure 8. Implantable TENGs with robust structure harvesting biomechanical energy from a–d) respiratory system. a–c) Reproduced with permission.[58] Copyright 2014, Wiley-VCH. d) Reproduced with permission.[59] Copyright 2018, American Chemical Society. e–g) Cardiovascular system. e) Reproduced with permission.[30] Copyright 2016, American Chemical Society. f) Reproduced with permission.[22] Copyright 2016, American Chemical Society. g) Reproduced with permission.[61] Copyright 2019, Wiley-VCH. and h) Digestive system. Reproduced with permission.[62] Copyright 2018, The Nature Publishing Group.

4.1.3. Digestive System

In 2018, Yao et al. presented a vagus nerve stimulation (VNS) system with characteristic of spontaneously responsive to stomach movement and battery-free based on the implantable TENG (Figure 8h), which realized effective weight control.[62] The VNS device was attached on the surface of the stomach with the size of ≈1.2 cm × 3 cm, harvesting the biomechanical from gastric peristalsis and generating electric pulses via contact separation of triboelectric layers (PTFE and Au) and electrode layer (Au). A bilateral VNS at the proximity of the gastroesophageal junction was wrapped by the Au leads. The Cu wire electrodes connected with Au lead for transmitting electrical signal. The PDMS and ecoflex were utilized as encapsulated layer with advantages of good biocompatibility, mechanical robustness, and flexibility. The output voltage of this VNS device can reach to ≈60 mV by continues stomach peristalsis at the frequency of 0.05 Hz. The average body weight of rat in experiment group was controlled at 350 g, 38% less than the control group. This work may provide a therapeutic strategy for obesity.

4.2. Biodegradable Implantable TENGs

Transient electronics usually consist of degradable organic or inorganic materials, which is an area of great interest for in vivo sensors and therapeutic devices.[63] Their physical structures can be degraded in a controlled manner in PBS or body fluid. Along with the development of transient electronics, biodegradable power sources have become urgent for applications such as environmentally friendly electronics and transient in vivo physiological monitoring and therapy. As an energy converting device, biodegradable implantable TENGs provide a feasible solution of energy supply for transient electronics and physiological monitoring. The component materials of these TENGs evolved from synthetic polymers to natural polymers. In this part, the presented TENGs have adopted the vertical contact–separation mode in most cases.

4.2.1. Synthetic Polymers

In 2016, Zheng et al. proposed a fully biodegradable TENG (2 cm × 3 cm) in vitro and in vivo consisting of synthetic polymers (poly(lactic-*co*-glycolic acid) (PLGA), poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV), and polycaprolactone (PCL)) (**Figure 9**a).[64] A tunable output voltage from 10 to 40 V in vitro was achieved by modulating the constituent materials. The degradation of the implantable TENG can be controlled by changing the encapsulation materials. The output performance of the PLGA-coated biodegradable TENG decreased significantly from 4 to 1 V in SD rats over 2 weeks. Integrating the biodegradable TENG with interdigital electrodes, neuron cells cultured on the surface of the interdigital electrode significantly aligned along the direction of the electric field generated by the biodegradable TENG. Neuron cell alignment is crucial for neural repair in the biomedical field. In the same year, Liang et al. developed a green and recyclable TENG that consisted of PVA and microstructure sodium alginate film as the friction materials and lithium (Li) and Al as the current collectors (Figure 9b).[65] When the device was soaked in water, the encasement rapidly dissolved. The device was completely dissolved in water within 10 min. In addition, the recyclable and green TENG generated a power density of 3.8 mW m^{-2} under the stimulation of finger motion. This device has potential transient applications as a power solution for biomedical implants. In 2018, Li et al. reported the photothermally tunable biodegradation of a TENG in SD rats (Figure 9c).[66] The biodegradable process of these TENGs was tuned using a mixture of Au nanorods, which was sensitive to near-infrared (NIR) light. The implanted TENG achieved normal function in vivo for ≈28 days without NIR illumination. After illuminating the TENG with NIR light, the electric output of the TENG decreased to 0 after 24 h. The TENG device can be mostly degraded in two weeks. These results indicated that NIR light can quickly trigger the in vivo degradation of a TENG. The maximum output of the TENG in vitro and in vivo reached 28 and 2 V, respectively. The researchers demonstrated the biological effect of the in vivo output voltage on fibroblast cells. The results showed that the electric output can significantly accelerate the cell migration across prefabricated scratches, which contributes to wound healing. This work demonstrated the feasibility of developing a photothermally tunable TENG as a transient power source for biomedical healthcare electronics.

4.2.2. Synthetic Polymers and Natural Polymers

In 2017, Pan et al. fabricated a fully biodegradable TENG using electrospun polylactic acid nanofiber and nanostructured gelatin films.[67] The gelatin and PLA polymer films were optimized to improve the output performance. The TENG was 4 cm × 4 cm. The output voltage, short circuit current, and maximum power density reached 500 V, 10.6 mA m^{-2}, and 5 W m^{-2}, respectively. The authors demonstrated that the TENG could be completely degraded in water after 40 days. The TENG has potential as a short-term power source for biomedical device.

4.2.3. Natural Polymers

In 2018, Wang et al. fabricated a triboelectric power generator based on engineered and laser-processed chitosan biopolymers (Figure 9d).[68] The authors found the chitosan nanocomposite treated with 10% showed the best output performance. The voltage and current were about 13.5 V and 42 nA, respectively, which suggested the tendency of the composite films to donate electrons. This chitosan-based TENG demonstrated here shows the feasibility of self-powered biomedical devices. In 2018, Jiang et al. proposed fully biodegradable implantable TENGs using natural materials (rice paper (RP), chitin, silk fibroin (SF), and egg white (EW), cellulose) (Figure 9e).[69] The biodegradable natural materials are biodegradable and easily processable, which make these materials suitable for implantable TENGs. The peak voltage, current, and power density reached 55 V, 0.6 μA, and 21.6 mW m^{-2} in vitro, respectively. The biocompatibility of these five natural materials have been demonstrated using L929 cells and hematoxylin and eosin (H&E)-stained

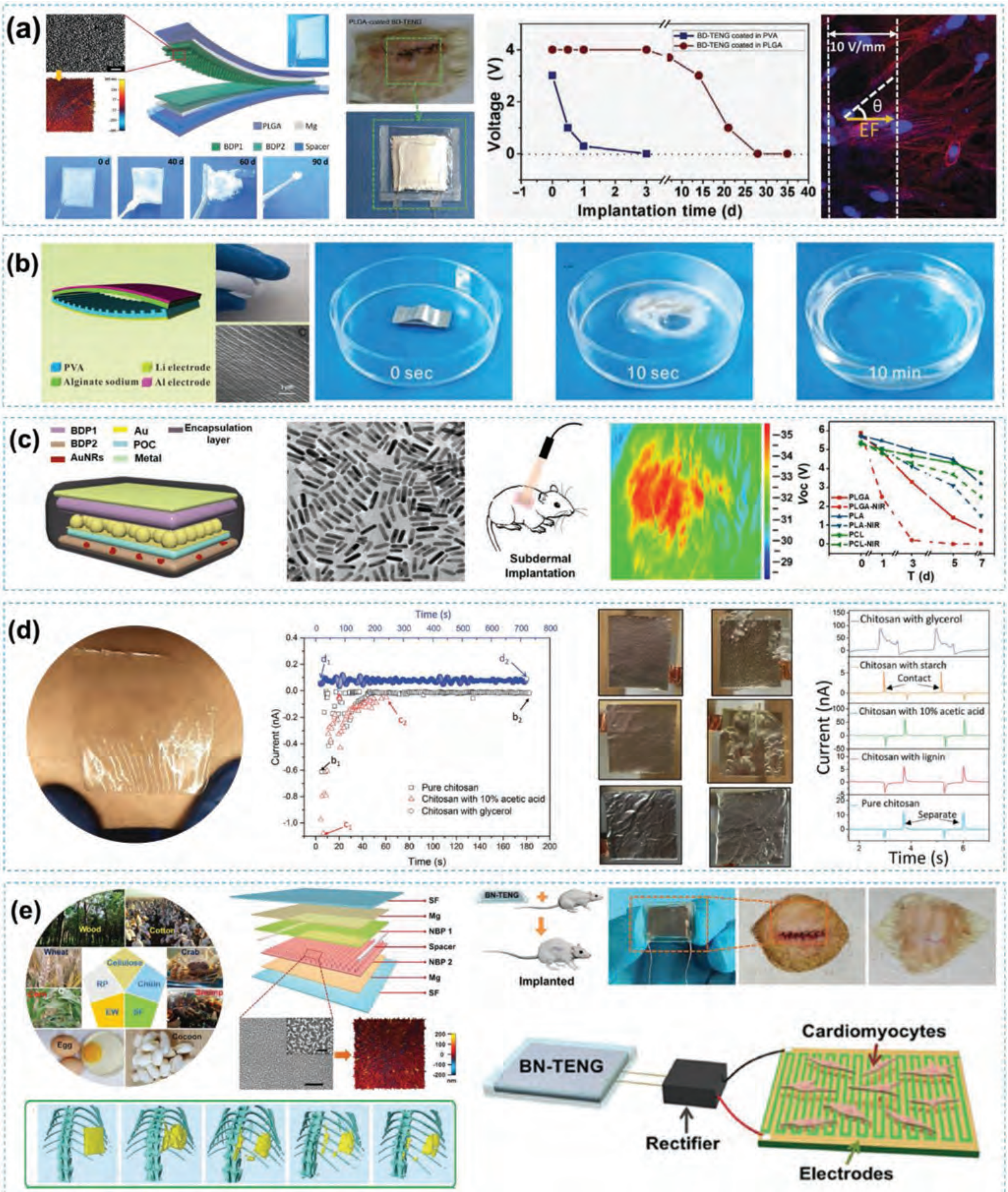


Figure 9. Implantable TENGs with biodegradable material include a–c) synthetic polymers. a) Reproduced with permission.[64] Copyright 2016, The American Association for the Advancement of Science. b) Reproduced with permission.[65] Copyright 2016, Wiley-VCH. c) Reproduced with permission.[66] Copyright 2018, Elsevier. d,e) Natural polymers for a variety of applications. d) Reproduced with permission.[68] Copyright 2018, Wiley-VCH. e) Reproduced with permission.[69] Copyright 2018, Wiley-VCH.

histologic section. After implanting the bioresorbable natural material-based TENG in vivo, the operation time of the BN-TENG can be tuned from days to weeks by methanol-treated silk fibroin (SF) encapsulation. The methanol can transform the molecular structure of silk fibroin from a random coil into a β-sheet conformation, which can strengthen the resistance of the natural material-based TENGs to interstitial fluid. The untreated SF-encapsulated natural material-based TENGs showed a short-term work time in PBS and in SD rats. The natural material-based TENGs encapsulated with untreated SF exhibited rapid degradation characteristics. A sharp decrease of output voltage occurred from 3 to 0.6 V after implantation for 24 h in SD rats. After 72 h, the output performance completely disappeared. Compared with untreated SF-encapsulated natural material-based TENGs, the output voltage of natural material-based TENGs with methanol-treated SF encapsulations decreased from 4.5 to 1.2 V at 11 days. After completing its purpose, the TENG was fully degraded and resorbed by SD rats. In this work, the authors demonstrated that the generated electricity of natural material-based TENGs can be used to regulate the beating rates of dysfunctional cardiomyocyte clusters, providing a new way to treat heart diseases such as bradycardia and arrhythmia.

The development of typical implantable TENGs in the last 5 years is summarized in **Table 2**. The feasibility of TENGs with the contact–separation mode and lateral sliding mode in vivo was proved in small animals (i.e., rat) in July 2014 and large animals (i.e., swine) in June 2016. The electric output of TENGs in vivo was significantly increased from 3.73 V by breathing in July 2014 to 14 V by heart beating in June 2016 for the output voltage, and 0.14 µA by breathing in July 2014 to 5 µA by heart beating in June 16 for the output current. The physical structure of TENGs changed from nondegradable in vitro in July 2014 to fully biodegradable in vivo in June 2016. The degradation manner of implantable TENGs changed from natural degradation in March 2016 to photothermally tunable biodegradation in October 2018. The constituent materials of TENGs became more and more diversified, from synthetic polymers (PDMS, PEFE, Parylene, PLGA, and PCL) in July 2014 to natural polymers (alginate sodium, chitosan, EW, RP, SF) in August 2018. The electric output from implantable TENG can generate different biological effects such as the orientated growth of nerve cells, beating rate regulation of cardiomyocyte clusters, healthcare monitoring and effective weight control. The fast development of implantable TENGs shows its great application potential in future biomedical electronics and healthcare monitoring.

5. Summary and Perspectives

TENG-based self-powered wearable and implantable electronics were rapidly developed in recent years due to their unique and effective energy harvesting from biomechanical motions. The application scenarios of wearable and implantable TENGs were extended from in vitro to in vivo. The operation functions of wearable and implantable TENGs changed from independent units to integrated systems. Additionally, the developed

Table 2. The summarization for the development of typical implantable TENGs in the last 5 years.

Features Date	Positions	Sizes [cm^2]	Materials	Working modes	Energy sources	Electric outputs	Applications	Degradability
July 2014[58]	Left chest, rat	1.2 × 1.2	PDMS, Al	Contact–separation	Breath	3.73 V 0.14 µA	Power pacemaker	None
March 2016[64]	Left chest, rat	2.0 × 3.0	PLGA, PCL PVA	Contact–separation	Breath	4 V	Stimulate Nerve cells	Yes
June 2016[22]	Heart, swine	4.0 × 6.0	PTFE, Al PDMS, Parylene	Contact–separation	Heart beating	14 V 5 µA	Wireless monitoring	None
August 2016[30]	Heart, swine	2.0 × 3.0	PTFE, Al PDMS, Parylene	Contact–separation	Heart beating	10 V 4 µA	Biomedical monitoring	None
February 2017[65]	None (in vitro)	10–30	PVA, Alginate sodium	Contact–separation	None	1.47 V 3.9 nA	None	Yes
March 2018[67]	None (in vitro)	4.0 × 4.0	Gelatin PLA	Contact–separation	None	500 V 10.6 mA m^{-2}	None	Yes
March 2018[68]	None (in vitro)	1.0 × 2.0	Kapton, Chitosan	Contact–separation	None	13.5 V 42 nA	None	Yes
August 2018[69]	Subcutaneous, rat	1.0 × 2.0	Cellulose, Chitin EW, RP, SF	Contact–separation	Body Movement	4.5 V	Stimulate cardiomyocytes	Yes
October 2018[66]	Subcutaneous, rat	2.0 × 2.0	PLGA, Au	Contact–separation	None	2 V 30 nA	Wound healing	Yes
November 2018[59]	Abdominal, rat	≈4.5	PET, PTFE, Cu Ecofle	Lateral sliding	Breath	2.2 V	Micropower supply	None
November 2018[61]	Heat chamber, swine	1.0 × 1.5	Al, PTFE PDMS	Contact–separation	Heart beating	6.2 V	EP monitoring	None
December 2018[62]	Stomach, rat	1.2 × 3.0	PTFE, Au PDMS Ecofle	Contact–separation	Peristole	60 mV	Stimulate vagus nerve	None

wearable and implantable TENGs successfully powered low energy consumption electronics such as smartwatches, smart glasses, pacemakers, nerve stimulators, and health monitoring devices. The broad applications of wearable and implantable TENGs can significantly impact future public life, from intelligent electronics to health supervision.

Nevertheless, considering that TENGs is a newly emerging technique for energy converting, therefore, extensive and in-depth studies are still needed to meet the requirements of diverse applications in future. The wearable and implantable TENGs as portable electronics have the same challenges as follows:

1) Efficient energy storage: Although the wearable and implantable TENGs have high output voltage, they are still insufficient to meet the real-time energy consumption for portable electronic. Therefore, the optimization of the output performance of wearable and implantable TENGs and the power management of the systems are required in further research. A novel universal power management of TENG has been demonstrated,[70] which is expected to solve the problems about efficient energy management for wearable and implantable TENG.
2) Miniaturization and integration: To meet the demands of dressing on body and implanting in vivo, wearable and implantable TENGs with smaller size are required. Therefore, it is important to find some methods to keep excellent output performance of the TENG after minimization. The potential solutions rely on the development of new material science and advanced manufacturing technologies. Furthermore, solving the challenge of miniaturization and integration of different units for multifunction is one tendency in future.
3) Longevity: Wearable and implantable TENG are still challenged by the longevity, including the stability and durability, due to the inherent limitations of recent materials used for fabricating these devices such as metallic organic polymers. More studies are required to improve the material performance and encapsulation technology to solve these issues.

Obviously, wearable and implantable TENGs have their own unique challenges for particular application scenario. The challenges of wearable TENG are as follows:

1) Antijamming capability: The wearable TENG can be dressed directly or indirectly on body as an active sensor. The jamming signal may be generated during complex sports patterns (e.g., walk, run, jump), disturbing the capture of target signals. How to solve the impact of jamming signal on the target signal is a challenge.
2) Adapting for the hard environment: The output of the wearable TENG is severely affected by the hard environment, such as humidity, chilliness, and high temperature. Therefore, it is of urgency to develop robust materials and encapsulation methods for wearable TENG.

The challenges of implantable TENG are as follows:

1) Biosafety: Biosafety is the most important criteria for implantable devices in vivo. At present, researchers just studied the biosafety and biocompatibility of implantable TENG within a short time (no more than one month) at the cellular and tissue level. Therefore, long-term biosafety of implantable TENG requires further evaluation. In addition, we need to further improve the biocompatibility and biosafety of materials used in implantable TENG, including friction layers, electrode layers and wires.
2) Efficient fixation: Efficient fixation between implantable devices and biological tissue is expected to further enhance the stability of long-term output and reduce the difficulty of anchoring operations. The fixation between devices and wet surfaces like biological tissues, is one of the key issues and challenges for the implantable TENG. Fortunately, some constructive research achievements will hopefully solve this fixation problem. For example, surfaces modified with micro/nano structures[71] and biocompatible tissue adhesives[72] can be used to improve the fixation ability of implantable devices to biological tissues. For implantable TENG, these technologies may also be introduced to improve the fixation ability between encapsulation material (PDMS) and organs.
3) Minimally invasive surgery: Minimally invasive surgery for implantable TENG can reduce the incidence of infection, which has great significance in clinic. In future, the direction for the miniaturization of implantable TENG, and the methods of combining it with a medical device, need to be studied in depth.

With the development of materials science, engineering technology, textile science, and biomedical techniques, TENG-based self-powered wearable and implantable electronic devices will add convenience and progress to modern life.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

implantable, portable electronics, self-powered, triboelectric nanogenerator, wearable

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