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Review

Advances in health rehabilitation devices based on triboelectric nanogenerators

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ABSTRACT

Timely information feedback combined with active therapeutic schedule can significantly shorten the rehabilitation period and reduce the pain of patients. Intelligent wearable and implantable medical electronic devices that can realize health information dynamic monitoring and disease treatment have attracted more and more attention. Triboelectric nanogenerator (TENG) is a novel technology for energy harvesting and information sensing. Due to its cost-effective, flexible structure and self-powered property, TENG has great application potential for personalized healthcare and mobile therapy. Herein, the recent key achievements of TENG technology in health rehabilitation are comprehensively reviewed with key considerations and case studies. The characteristics and corresponding technologies of TENG applied in self-powered sensing, integrated system and bioelectric stimulation are introduced and analyzed. Finally, the existing limitations and the prospect of further development are put forward.

1. Introduction

Health rehabilitation usually takes a long time, especially for chronic diseases. Timely information feedback combined with active treatment methods can significantly shorten the rehabilitation period, alleviate financial and physical suffering of patients [1–3]. Therefore, there is an urgent need to develop efficient and cost-effective technologies for health monitoring and rehabilitation. The rapid development of Internet of Things and wearable/implantable devices provides an effective way for personalized healthcare [4–8]. Wearable or implantable health monitoring systems use sensors to interact with the body and extract physical and physiological signals in real time. The extracted signals will be transmitted wirelessly to mobile phone applications and cloud platforms, and processed into actionable health information using big data analysis or artificial intelligence to provide users with remote disease diagnosis and treatment, as well as health management services [9,10]. The continuous collection, processing, and wireless transmission of data pose higher requirements for the power supply of health monitoring equipment. Although rapid advances in electronic technology have succeeded in reducing the power consumption of devices, extending continuous operating time remains a huge challenge. The demand for energy supply of massive and disordered distributed health monitoring devices in the Internet of Things has become one of the key issues hindering the development of personalized medicine [11]. Most existing health monitoring devices still rely on rechargeable batteries with limited life like lithium batteries, which is difficult to meet the needs of personalized medical devices for mobility, wearable/implantable, and integrability [12]. Especially for implanted devices, the secondary surgery required for battery replacement will greatly increase the risk of infection, placing a physical and financial burden on the patient [13]. The further development of personalized medical devices urgently requires the development of sustainable and renewable distributed energy sources to cope with the constraints of traditional power supply methods.

Triboelectric nanogenerators (TENG), a novel energy harvesting and information sensing technology, convert various types of mechanical energy into electricity via coupling of triboelectric effect and electrostatic induction [14–18]. Due to its low cost, simple manufacturing,

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diverse working modes, high energy conversion efficiency, wide material selection, flexible structure and other advantages, it has been widely applied in fields such as environmental energy collection, personalized healthcare, Internet of Things, and self-powered sensing technology [19–23]. TENG can generate electrical signals in response to human body stimuli, act as an active sensor for dynamic monitoring of health information, and can also serve as a sustainable power source for medical devices [16,24–27]. In addition, the electrical signals generated by TENG can be directly used to stimulate biological cells, nerves, tissues and organs for electrical stimulation therapy [28–33]. Combined with cloud computing, big data and artificial intelligence technologies, TENG and TENG-based body area networks will play a crucial role in personalized medicine and mobile therapy (Fig. 1).

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This review aims to overview the applications of TENGs in health rehabilitation. Hence, after briefly introducing the principles and working modes of TENG, the research progress of TENG in health rehabilitation is introduced from the three main functions: self-powered sensors, integrated systems and bioelectrical stimulation. In the self-powered sensor section, the application of TENG in monitoring physiological signals such as respiration, heart rate and pulse, as well as its use in assistive devices, is presented. In the integrated system section, the application of TENG as an energy harvesting unit in self-powered sweat monitoring, microneedle drug delivery system and cardiac pacing system is emphasized. In the bioelectrical stimulation section, the research progress of TENG as an electrical stimulator in wound healing, muscle control nerve regulation and bone regeneration are mainly introduced. Eventually, the existing challenges and the prospective to the future are also presented.

2. Triboelectric nanogenerator

2.1. Theory of TENG

The working mechanism of TENG mainly relies on triboelectric and electrostatic coupling effects. Triboelectrification refers to the phenomenon that two materials with different electron binding ability contact and rub with each other, so that electrons are transferred from one material surface to another, and two materials are charged with equal amounts of opposite charges. Electrostatic induction refers to that when charged object and uncharged conductor are close to each other, the charge inside the conductor will be redistributed due to the interaction between charges. The opposite charges are adsorbed near the charged object, while the same charges are repelled to the opposite end of the conductor, creating an induced potential difference that drives the flow of electrons. TENG is the coupling of triboelectric and electrostatic induction for energy conversion. It first accumulates charges on the two

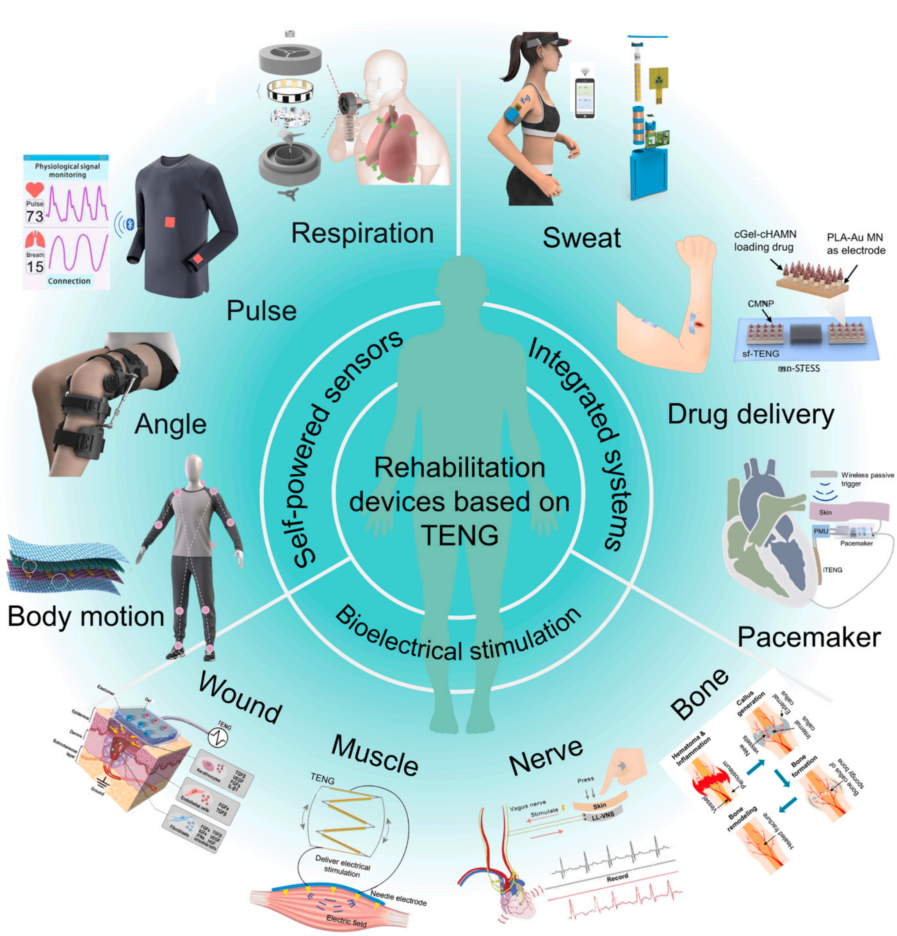

Fig. 1. Overview of the role played by TENG in the health rehabilitation, including self-powered sensors, integrated systems and bioelectrical stimulation.

triboelectric layers via the triboelectric effect, and then outputs electricity via electrostatic induction between the moving triboelectric layer and the electrodes. The research team of Professor Zhong Lin Wang reported the first TENG in 2012 [45]. The structure of TENG consists of polymethyl methacrylate (PMMA) film and polyimide (Kapton) film, and the back of the film is coated with metal electrodes. The open-circuit voltage of the first TENG is about 3.3 V and the power density is 10.4 mW·cm^{-3}, opening a breakthrough avenue for energy harvesting technology. Due to the characteristics of cost-effective, simple fabrication, diverse working modes, and high energy conversion efficiency, TENG has been widely used in environmental energy harvesting [17,46,47], Internet of Things [48,49], medical devices [31,32], and self-powered sensing technology [15,50]. TENG can respond to low-frequency stimuli of human motion and harvest biomechanical energy. Its high voltage and low current output characteristics have unique advantages in biosensing and bioelectric stimulation therapy. Table 1 summarizes and compares the characteristics of several energy harvesting technologies applied in healthcare.

2.2. Working modes of TENG

2.2.1. Vertical contact-separation mode

The contact-separation mode is the basic mode of the TENG, whose structure consists of two materials with different triboelectric polarities, with the electrodes are located on the backside of the triboelectric materials (Fig. 2a). Two different triboelectric materials come into contact under the action of external excitation, and the surface charges are transferred due to the triboelectric effect, so that the surfaces of the two triboelectric materials are respectively charged with equal amounts of positive and negative charges, forming a potential difference. When the external excitation is released, two different triboelectric materials are separated. Due to the potential difference, electrons flow from high potential to low potential through the external circuit, achieving charge balance. When the external excitation is applied again, the induced charges transferred back to the original electrodes, which also generates a reverse current flow. When repeated cyclic contact separation occurs, the TENG can generate a periodic alternating current (AC) output. The TENG in this mode has a simple structure and high instantaneous power, making it suitable for human body motion energy harvesting, pressure sensors, etc.

2.2.2. Horizontal-sliding mode

The TENG structure of the horizontal-sliding mode is similar to that of the contact-separation mode, as shown in Fig. 2(b). The two triboelectric materials slide relative to each other under an external force parallel to the material, thereby generating triboelectric charges, which breaks the restriction that TENG can only operate in the vertical direction in the contact-separation mode. When the two triboelectric layers are in full contact, the two contact surfaces will generate equal amounts of positive and negative charges due to the difference in triboelectric polarity. When external mechanical action makes the contact surface slide horizontally, polarization is formed in the horizontal direction, and induced charge is driven to move, resulting in induced potential difference. When an external load is connected, the free electrons in the circuit are driven to cancel the induced potential difference, thereby generating a current output. If the two friction surfaces periodically slide horizontally under the action of external mechanical energy, TENG will generate continuous electrical energy output. The TENG in the horizontal-sliding mode can generate continuous electric energy output at high frequency, and its energy conversion efficiency is higher than that in the contact-separation mode, which is more widely used in practical applications. Various structures have been developed for TENG based on horizontal sliding mode, such as gate electrode structure [51–53], rotating disk structure [54–56], rotating column structure [57–59], liquid friction layer structure [60–62] etc. to adapt to different application scenarios.

2.2.3. Single-electrode mode

The structure of single-electrode mode TENG is shown in Fig. 2(c). The conductive electrodes are located on the backside of the polymer film. When connected to an external load, the conductive electrodes are grounded to form a circuit. Since the polarity of materials between the freely moving object and the polymer film is different, equal and opposite charges are generated at contact. When the two contact surfaces are separated, there will be an electrical potential difference between the electrode and the ground wire, which drives the flow of electrons and produces a current output. Because the structure of TENG is simplified, it is more widely applied and greatly enriches the way of collecting mechanical energy. However, due to the existence of electrostatic shielding effect, the electrical output of the single-electrode TENG is obviously lower than that of the contact-separation mode and the horizontal-sliding mode, which limits the application of single-electrode TENG to a certain extent.

2.2.4. Freestanding triboelectric-layer mode

The TENG of freestanding triboelectric-layer mode is made up of two fixed electrodes and a triboelectric layer, with a small gap between the two electrodes, as shown in Fig. 2(d). Two triboelectric materials are in contact and charged in the air, one friction material acting as a separate friction layer and the other triboelectric material attached to the two electrodes as an induction layer. The motion of the independent triboelectric layer causes the charge to change, creating an induced potential difference between the two electrodes that drives the electrons. Periodic motion of the independent triboelectric layer results in periodic transfer of electrons between the two electrodes, resulting in an AC output. It can achieve relatively higher energy conversion efficiency compared to other modes of TENG. In addition, the TENG can operate not only in contact conditions with two triboelectric layers, but also in non-contact

Table 1
Summary and comparison of the energy harvesting technologies applied in healthcare.

Energy Technology	Working Mechanism	Power Characteristic	Open-circuit Voltage	Short-circuit Current	Output Power
TENG	Triboelectric effect and electrostatic induction	AC[e]	High	Low	Low
PENG[a]	Piezoelectric effect	AC	Medium	Low	Low
EMG[b]	Electromagnetic induction	AC	Low	High	High
PyNG[c]	Pyroelectric effect	AC	Medium	Low	Low
TEG[d]	Seebeck effect	DC[f]	Low	Medium	Medium
Solar cell	Photovoltaic effect	DC	Low	High	High
Biofuel cell	Redox reaction	DC	Low	High	High

[a] PENG: Piezoelectric nanogenerator.
[b] EMG: Electromagnetic generator.
[c] PyNG: Pyroelectric nanogenerator.
[d] TEG: Thermoelectric generator.
[e] AC: Alternating current.
[f] DC: Direct current.

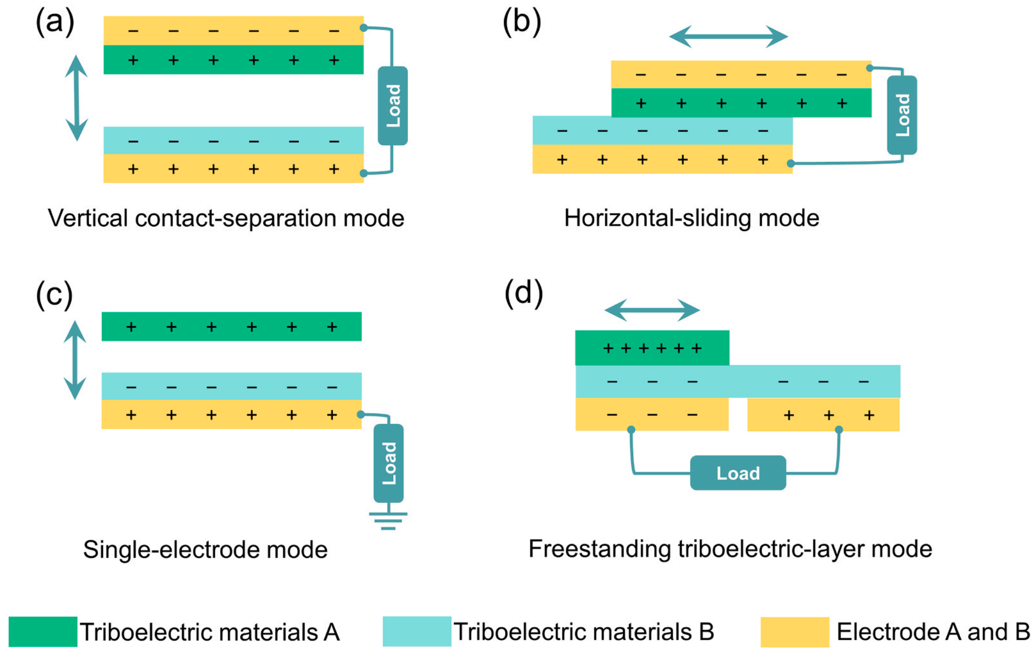

Fig. 2. Four fundamental working modes of TENG. (a) Contact-separation mode. (b) Horizontal-sliding mode. (c) Single-electrode mode. (d) Freestanding triboelectric-layer mode.

conditions, which can greatly reduce the materials wear and energy consumption, and extend the service life. TENG with freestanding triboelectric-layer mode is mostly used to harvest various forms of mechanical energy.

3. TENG-based self-powered sensor in health rehabilitation

3.1. Sensors for physiological signal sensing

TENG can directly convert mechanical stimuli into electrical signals and thus has outstanding potential for the development of self-powered sensors, such as tactile sensors [63–65], pressure sensors [66–68], motion sensors [69–71], etc. Respiratory, heart rate, pulse and other parameters can reflect the physiological characteristics of the human body. If these physiological parameters can be easily and precisely collected, it would be beneficial to timely identify and provide feedback on the problems encountered by patients during the rehabilitation process. As a unique mechanic-electrical conversion technology, TENG has been widely used in sensing of physiological signals. For example, Peng et al. developed a highly sensitive, self-powered e-skin based on TENG employing electrospinning technology for respiratory monitoring [72]. The TENG-based e-skin uses multi-layer polyacrylonitrile (PAN) and polyamides 66 (PA 66) nanofibers as triboelectric materials, and deposits gold as electrodes, as shown in Fig. 3(a). Numerous spatial micro-nano porous structures are created between the interlacing nanofibers, offering a high specific surface area for contact electrification and numerous interfibrous capillary channels for heat and humidity transfer, which not only gives the electronic skin good air permeability but also improves the power output and pressure sensitivity. With an excellent pressure sensitivity of 0.217 kPa^{-1}, the e-skin, combined with the developed real-time respiratory monitoring system, can effectively identify obstructive apnea. Liu et al. developed a portable turbine spirometer based on a floating rotating independent TENG for respiratory flow measurement and pulmonary function assessment (Fig. 3b) [34]. The turbine rotor uses the triboelectric effect and electrostatic induction to transform the breathing airflow into a full sine signal when it passes through. Combining deep learning, an intelligent pulmonary function assessment system was designed, which successfully predicted flow and calculated pulmonary function parameters. The portable intelligent pulmonary function assessment system has been further validated in pulmonary function testing and evaluation of COVID-19 patients, providing the possibility for evaluating the rehabilitation trend and long-term follow-up of COVID-19 recovered patients.

Pulse wave is one of the most intuitive indicators to reflect the cardiovascular status. Xu et al. reported a self-powered ultra-sensitive pulse sensor (SUPS) for multi-indicator cardiovascular monitoring (Fig. 3c) [73]. The TENG is composed of micro-structured triboelectric layers, sponge spacer layers and electrostatic shielding layers. Thanks to the microstructure of the material surface and the structural design of the device, this SUPS has ultra-high sensitivity (10.29 $nA{\cdot}kPa^{-1}$) and fast response time (30 ms). SUPS can accurately detect the peak value of different pulse waves, and extract cardiovascular indicators such as pulse wave velocity, heart rate, blood pressure, etc. from the difference of characteristic pulse peak positions, which is expected to find applications in the prevention and complementary treatment of cardiovascular disease. Zou et al. developed a self-powered pulse sensor based on a combination of piezoelectric and triboelectric effects for detection of radial pulse waveforms (Fig. 3d) [74]. A flexible self-arching structure is created according to the stress mismatch at the PDMS/Ecoflex interface, which can take the role of spacers in conventional TENG devices. To increase sensing performance even further, PVDF film is implanted into the self-arching structure to build a composite nanogenerator, which can improve the output, signal-to-noise ratio, and stability of pulse detection.

Smart textiles have the advantages of softness, light weight and good breathability, so they have great application potential in wearable health detection devices [75–79]. Fan et al. developed an all-textile sensor array based on triboelectric effect that can simultaneously detect multiple physiological signals (Fig. 3e) [35]. The all-textile sensing array is made of conductive yarn and nylon yarn woven with full cardigan stitches. It has a sensitivity of 7.84 $mV{\cdot}Pa^{-1}$ to tiny pressures on the skin. It can be easily integrated into different parts of the garment for aesthetic design, which correspond to pulse waves in the neck, wrists, fingertips and ankles, as well as breathing waves in the abdomen and chest. A further intelligent health monitoring system based on the all-textile sensor array sustainably acquires and preserves physiological signals for analysis and evaluation of cardiovascular disease analysis and sleep apnea syndrome.

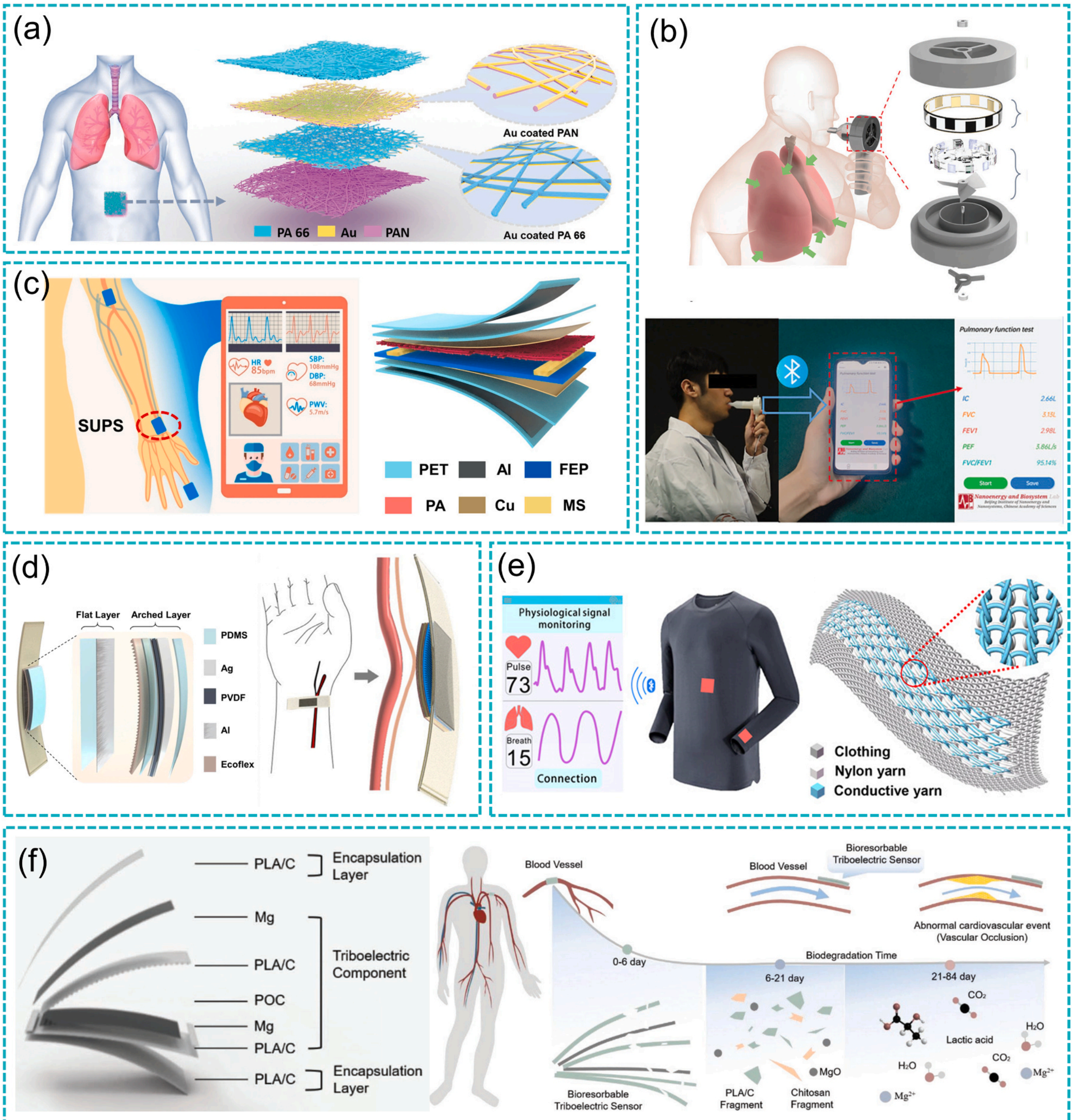

Fig. 3. (a) All-nanofiber self-powered respiratory sensor. (b) Portable self-powered turbine spirometer. (c) Self-powered ultrasensitive pulse sensors cardiovascular monitoring. (d) The flexible self-arched pulse sensor. (e) All-textile pressure sensors. (f) The bioresorbable dynamic pressure sensor. (a) Reproduced with permission [72]. Copyright 2021, Wiley-VCH. (b) Reproduced with permission [34]. Copyright 2023, Wiley-VCH. (c) Reproduced with permission [73]. Copyright 2021, Elsevier. (d) Reproduced with permission [74]. Copyright 2020, Elsevier. (e) Reproduced with permission [35]. Copyright 2020, American Association for the Advancement of Science. (f) Reproduced with permission [85]. Copyright 2021, Wiley-VCH.

Implantable bioabsorbable sensors can not only continuously monitor vital physiological signals in situ, but also degrade in vivo and be absorbed by the body after their service life, avoiding secondary surgery [80–84]. Ouyang et al. proposed an implantable bioabsorbable triboelectric sensor (BTS) [85]. The BTS uses the bioabsorbable material polylactic acid chitosan (PLA/C) as the triboelectric layer, and the magnesium (Mg) layer deposited on the backside as the electrode. Besides, Mg is deposited on another PLA/C film, serving as electrode and triboelectric layer. Poly(1,8-octane diol-*co*-citric acid) (POC) serves as the bonding layer, and the entire device is enclosed in PLA/C. BTS can effectively identify abnormal vascular occlusion events with a high sensitivity of 11 mV·mmHg^{-1}. BTS can last up to five days in the body and are absorbed at the end of their lifespan. This self-powered sensor has achieved full bioabsorbability in vivo for the first time and is anticipated to be employed as bioabsorbable electronic devices in vivo for postoperative care.

3.2. Sensors for rehabilitation assistive devices

In the process of rehabilitation, accurate rehabilitation assessment is indispensable and crucial for effective treatment. Luo et al. reported on a portable, modular, wearable knee brace for self-assessment of recovery in total knee arthroplasty patients [36]. The system comprises of an active angle sensor for knee bending detection and a force sensor for measuring muscle strength, as shown in Fig. 4(a). Force and angular resolutions were 0.01 N and 1°, respectively. The angle sensor is composed of grid structure TENG. Liquid lubrication and sponge buffering are adopted to ensure the stability of the TENG-based angle sensor. The knee support system can assess the patient’s daily activities after surgery, providing a new method for monitoring the patient’s

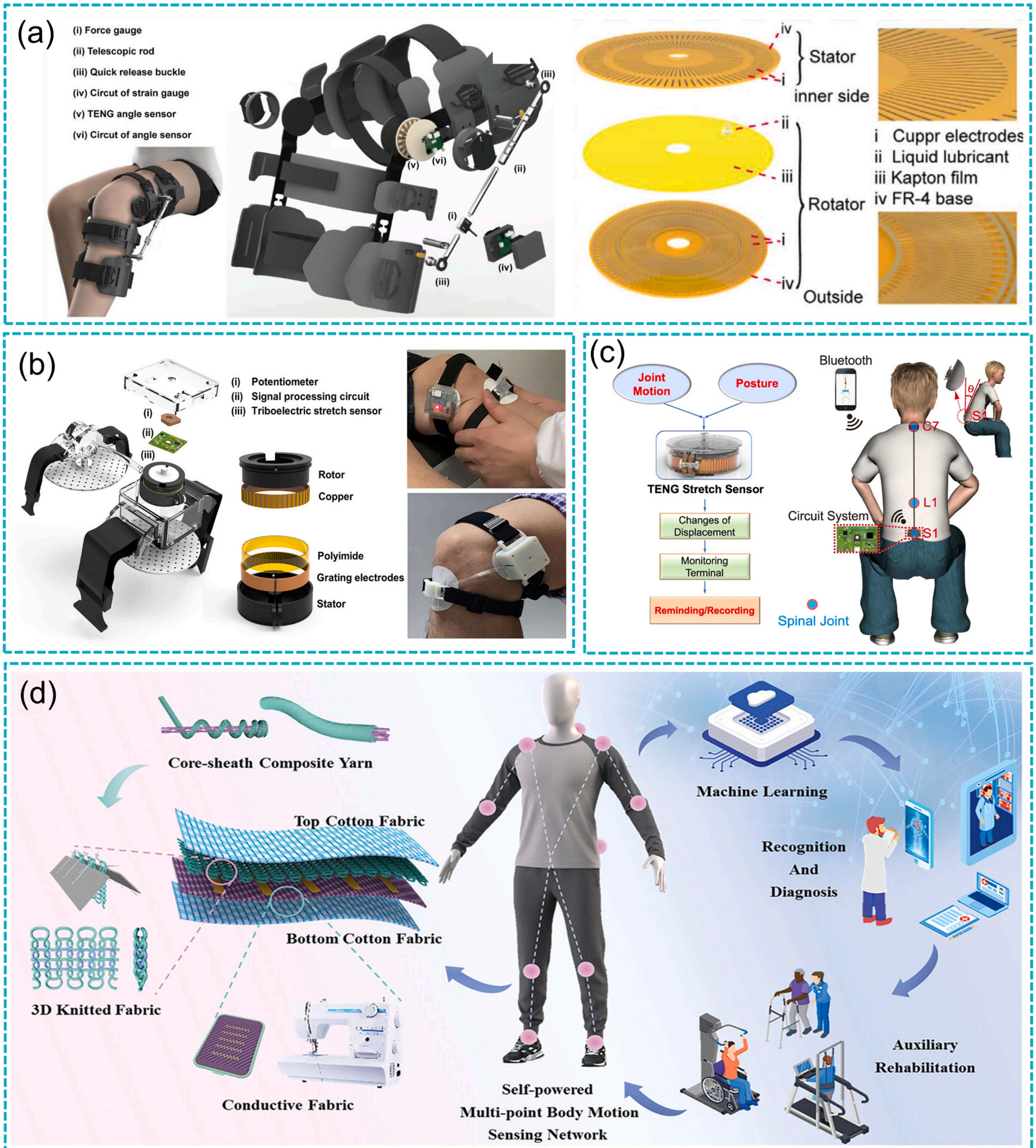

Fig. 4. (a) Conjoint isometric myodynamia and real-time rotation sensing system. (b) High-precision wearable displacement sensing system. (c) Wearable badge reel sensor for spine bending or stretching. (d) Self-powered body motion sensor network for gait recognition and rehabilitation training. (a) Reproduced with permission [36]. Copyright 2022, Wiley-VCH. (b) Reproduced with permission [86]. Copyright 2023, American Chemical Society. (c) Reproduced with permission [87]. Copyright 2021, Springer Nature. (d) Reproduced with permission [37]. Copyright 2023, Wiley-VCH.

postoperative and longitudinal rehabilitation.

Human movements such as joint bends and spinal contortions contain information useful for the diagnosis, rehabilitation and prevention of muscle, skeletal, and neurological diseases [88,89]. Yang et al. reported a high-precision wearable displacement sensing system based on a TENG stretch sensor (Fig. 4b) [86]. The stretch sensor is composed of a grating structure TENG with a high displacement resolution of 0.2 mm. The wearable displacement sensing system can be attached to a patient's knee to help doctors diagnose anterior cruciate ligament injuries. The evaluation of knee displacement by the Lachman test showed that the system has high accessibility and accuracy, and can be used as a complement to existing arthroscopes. Based on a similar grating structure TENG, Li et al. devised a badge-reel-like stretch sensing device for monitoring of knee/arm bends, neck/waist twists, etc. (Fig. 4c) [87]. The device stretches and shrinks in sync with the bending and stretching of human subjects, with high sensitivity (8 $V \cdot mm^{-1}$), high resolution (0.6 mm), excellent robustness, and low hysteresis. It can be used as a rehabilitation stent to record the patient's joint movement in real time during the longer recovery time after injury.

Gait analysis has been an important method in the diagnosis and evaluation of skeletal, muscular and nervous system diseases [90–92]. For gait recognition and assisted rehabilitation training, Wei et al. proposed a self-powered multi-point body motion sensor network (SMN) with a full-textile structure (Fig. 4d) [37]. SMN is prepared using conventional knitting techniques and rising digital embroidery techniques, which preserve great air permeability (165 $mm \cdot s^{-1}$) and moisture permeability (318.0 $g \cdot m^{-2} \cdot h^{-1}$) in addition to having excellent sensitivity (1.5 $V \cdot kPa^{-1}$). To examine the amplitude and time of the limb movements, the sensor nodes of the SMN are positioned at the joints. The system can analyze the periodic signals and dynamic parameters of limb swing in conjunction with machine learning, and the accuracy of the five pathological gaits is up to 96.7 %, including gluteus maximus gait, floor dragging gait, scissor gait, Parkinson gait, and straddle threshold gait, which provides a new approach for intelligent personalized medicine.

4. TENGs based integrated system in health rehabilitation

4.1. Self-powered sweat monitoring system

Sweat contains abundant health-related biomarkers, such as electrolytes, proteins, amino acids, hormones, etc. [93–96]. Wearable sweat sensors enable continuous, in-situ monitoring of these biomarkers at the molecular level, providing a strong data base for assessing health and optimizing exercise performance [97–101]. Song et al. constructed a fully self-powered wireless wearable sweat monitoring system by seamlessly integrating a high-efficiency TENG, a low-power wireless sensing circuit, and a microchannel sweat sensor patch (Fig. 5a) [102]. The system efficiently converts the mechanical energy of human movement into electrical energy via a flexible, freestanding-mode TENG. The TENG is fabricated using flexible printed circuit board technology, and consists of an interdigitated electrode stator and a grating pattern slider with polytetrafluoroethylene (PTFE) and copper as the tribo-pairs. By optimizing the distance between interdigitated electrodes, a maximum output power of 416 $mW \cdot m^{-2}$ was achieved. The power management module, sensing analog circuits and Bluetooth are integrated in the low-power circuit board for energy management, signal processing and wireless communication. The microchannel sweat sensing patch can be tightly attached to the skin surface to automatically collect and analyze sweat. The system can dynamically detect sweat biomarkers, such as pH and Na^+, and transmit the data wirelessly to the user interface. During the 30-minute jog, the system recorded 5

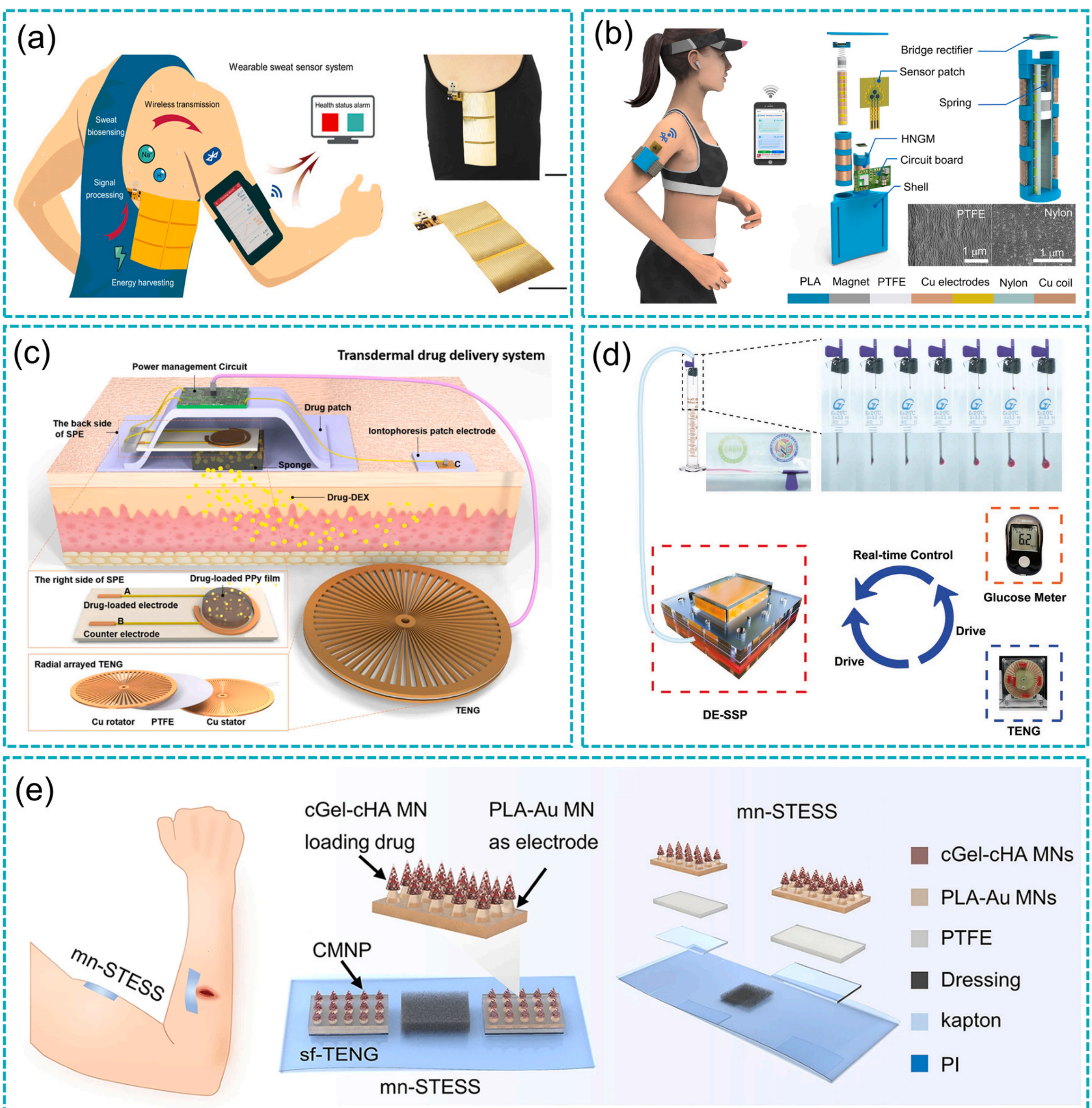

Fig. 5. (a) Wearable sweat sensor powered by human motion. (b) The self-powered wearable sweat sensor. (c) Self-powered, on-demand transdermal drug delivery system. (d) Self-powered syringe pump for insulin pump therapy. (e) Microneedles-based self-powered transcutaneous electrical stimulation. (a). Reproduced with permission [102]. Copyright 2020, American Association for the Advancement of Science. (b) Reproduced with permission [44]. Copyright 2022, Wiley-VCH. (c) Reproduced with permission [43]. Copyright 2019, Elsevier. (d) Reproduced with permission [103]. Copyright 2023, Wiley-VCH. (e) Reproduced with permission [104]. Copyright 2022, Springer Nature.

measurements, proved itself to be fully functional.

While it is challenging to effectively portray the changing trend of biomarkers because of TENG's fundamentally low output power and the corresponding excessively extended sensing duration. Gai et al. proposed a wearable sweat sensing device based on hybrid nanogenerator modules (HNGMs) (Fig. 5b) [44]. The HNGM was prepared by hybridization of TENG with electromagnetic generator (EMG) using the structure design of spring-mass coupling. The TENG also has an interdigital electrode structure with PTFE and nylon films as the tribo-pairs. As the self-sustainable power source for wearable sweat sensing device, HNGM can effectively harvest the vibration energy from human motions. On-body real-time sweat analysis shown that the HNGM-driven wearable sweat sensing device can selectively detect Na^+ and K^+ in sweat and shorten the sensing period to 1 min.

4.2. Self-powered drug delivery system

The electrical stimulatory drug delivery system activates the electrically sensitive drug carrier with an electric field or current and releases the drug as needed at the target spot [105–108]. By combining with sensors or microchips, the electrical stimulated drug delivery system can achieve repeated controlled drug release and information feedback, so as to lessen the harmful side effects of medications on the body and increase their therapeutic impact [109–112]. Ouyang et al. described a TENG-based on-demand transdermal drug delivery system (Fig. 5c) [43]. The system comprises of a rotating disk structure TENG, a power management module and a transdermal patch. The energy harvested by TENG from human movement is converted into the required direct current through the power management module. A polypyrrole (PPy) film coated screen-printed electrode serves as a drug carrier for Dexamethasone Sodium Phosphate (DEX-P) and 6-carboxyfluorescein (FLU). Under certain electric field stimulation, the drug DEX-P can be released from the PPy membrane into the phosphate-buffered saline soaked sponge, and active iontophoresis can be carried out under further electrical stimulation to improve the delivery efficiency of the drug in the sponge. The findings imply that TENG can be employed for drug release on demand. The medication release rate is 3 $g{\cdot}cm^{-2}$ when the TENG is manually rotated for 1.5 min, and it can be precisely adjusted to be between 0.05 and 0.25 $g{\cdot}cm^{-2}$ by varying the charging time of TENG or the resistance of power management. Additionally, in vitro experiments on pig skin, drug delivery using TENG was more efficient.

Microneedles, combined the advantages of both transdermal patch and hypodermic syringe, can deliver drugs directly into the epidermis or dermis without hitting nerve endings [113–117]. It has the merits of minimally invasive, slight pain, and high patient compliance, and is a promising drug delivery method [106,118]. By combining a sliding free-standing TENG with a microneedle patch, Yang et al. constructed a self-powered transcutaneous electrical stimulation system for improving the pharmacodynamics of epidermal growth factor (EGF) in wound healing (Fig. 5e) [104]. The TENG is composed of triboelectric layer, dielectric layer and electrode layer. The polyimide (PI) film acts as the triboelectric layer, and the PTFE film covers the Kapton strip as the dielectric layer. Polylactic acid coated gold microelectrode array patches (PLA-Au MNP) was used as electrodes. The drug-loaded cross-linked gelatin and crosslinked hyaluronic acid microneedles (cGel-cHA MNs) were covered on PLA-Au MNP to make the composite microneedle patch. The composite microneedle patches can continuously release epidermal growth factor into the skin for 24 h. The biosafe micro-current generated by finger sliding is introduced into the dermis by microneedles for electrical stimulation. Electrical stimulation provided by TENG acts as an electrical "adjuvant" to increase the intermolecular distance with glutathione by promoting the movement of EGF, hence preserving the stability of exogenous EGF. Electrical stimulation concurrently increased the expression of the EGF receptor to counteract receptor desensitization and boost EGF effectiveness, according to cell and animal studies. This work on combinatorial therapeutic strategies opens up a new era for improving drug pharmacodynamics.

Dielectric elastomer is a kind of electroactive functional polymer that can produce large deformation under the electric field [53,119–121]. Wei et al. constructed a self-powered soft syringe pump for insulin pump therapy by combining a dielectric elastomer actuator with a high-voltage TENG (Fig. 5d) [103]. The syringe pump consists of dielectric elastomer (VHB 4910) film, drug-carrying liquid sac, water-filled balloon, PMMA substrate and some support frames. The TENG uses a rotating disk structure with nylon and Kapton as friction pairs. The TENG can output a voltage of 20 kV. The dielectric elastomer film expands under electrical stimulation. Under the pressure of the water-filled balloon, the dielectric elastomer film deforms to one side of the drug-carrying liquid sac, and the liquid sac is squeezed to achieve drug injection. The infusion tube is equipped with a check valve to prevent the backflow of liquid medicine. The system has a maximum pump volume of 303.7 μL and can effectively adjust by adjusting the voltage output of the TENG.

4.3. Self-powered cardiac pacing system

Artificial cardiac pacemakers use electrical impulses to regulate and stabilize the rhythm of the heartbeat, thereby treating cardiac dysfunction due to arrhythmias [22,33,122]. Battery-powered pacemakers have a limited lifespan and require additional surgery to replace them, which brings pain and risk to patients [123]. Zheng et al. report the first implantable TENG to achieve biomechanical energy harvesting in a living animal and successfully drive a pacemaker by storing the harvested energy in a capacitor (Fig. 6a) [124]. The implantable TENG adopts a contact-separation working mode, pyramid array PDMS and aluminum foil as tribo-pairs, and gold and aluminum foils as electrodes. The TENG is sealed in polymer to isolate the surrounding media and improve robustness. TENG was implanted subcutaneously in the left chest of a rat to harvest the biomechanical energy generated by their respiration, with a power density of up to 8.44 $mW{\cdot}m^{-2}$. The harvested electrical energy is stored in a capacitor, which successfully power a prototype pacemaker to regulate the heart rate of the rat. This work is a pioneering achievement for TENG in the application of implantable self-powered medical device.

Then, Ouyang et al. presented a symbiotic implantable pacemaker powered by TENG that harvests the biomechanical energy of the heartbeat and stimulates the heart with the harvested electrical energy (Fig. 6b) [42]. The implantable TENG incorporates PTFE and Al as triboelectric materials, as well as a three-dimensional elastic sponge (ethylene-vinyl acetate, EVA) and a memory alloy ribbon (titanium) as a spacer and keel. And it is packaged with Teflon and PDMS. After implantation in pigs, the energy generated each cardiac cycle is 0.495 μJ, which is greater than the 0.377 μJ necessary for endocardial pacing. In a large animal model, the pacemaker effectively performed cardiac pacing and sinus arrhythmia correction. The energy source and stimulation target of TENG based cardiac pacemakers are both the heart, forming an interconnected symbiotic system with the body. This work is the first true self-powered pacemaker and is a milestone in the development of implantable self-powered medical devices.

Ryu et al. described an implantable TENG driven by the inertia of body motion and gravity, and implement a self-rechargeable pacemaker system (Fig. 6c) [125]. The TENG uses amine functionalized polyvinyl alcohol ($PVA\text{-}NH_2$) and perfluoroalkoxy (PFA) as triboelectric materials. The maximum volumetric power density of the five-stacked TENG is 4.9 $\mu W{\cdot}cm^{-3}$. When fully encapsulated TENG is implanted into different parts of a large animal, the TENG has significant power performance when driven by biomechanical energy and inertia. TENG can charge lithium-ion batteries for cardiac pacemakers with the aid of power management integrated circuits. The self-rechargeable pacemaker successfully demonstrated the VOO and VVI mode of mongrel dogs in the case of bradycardia.

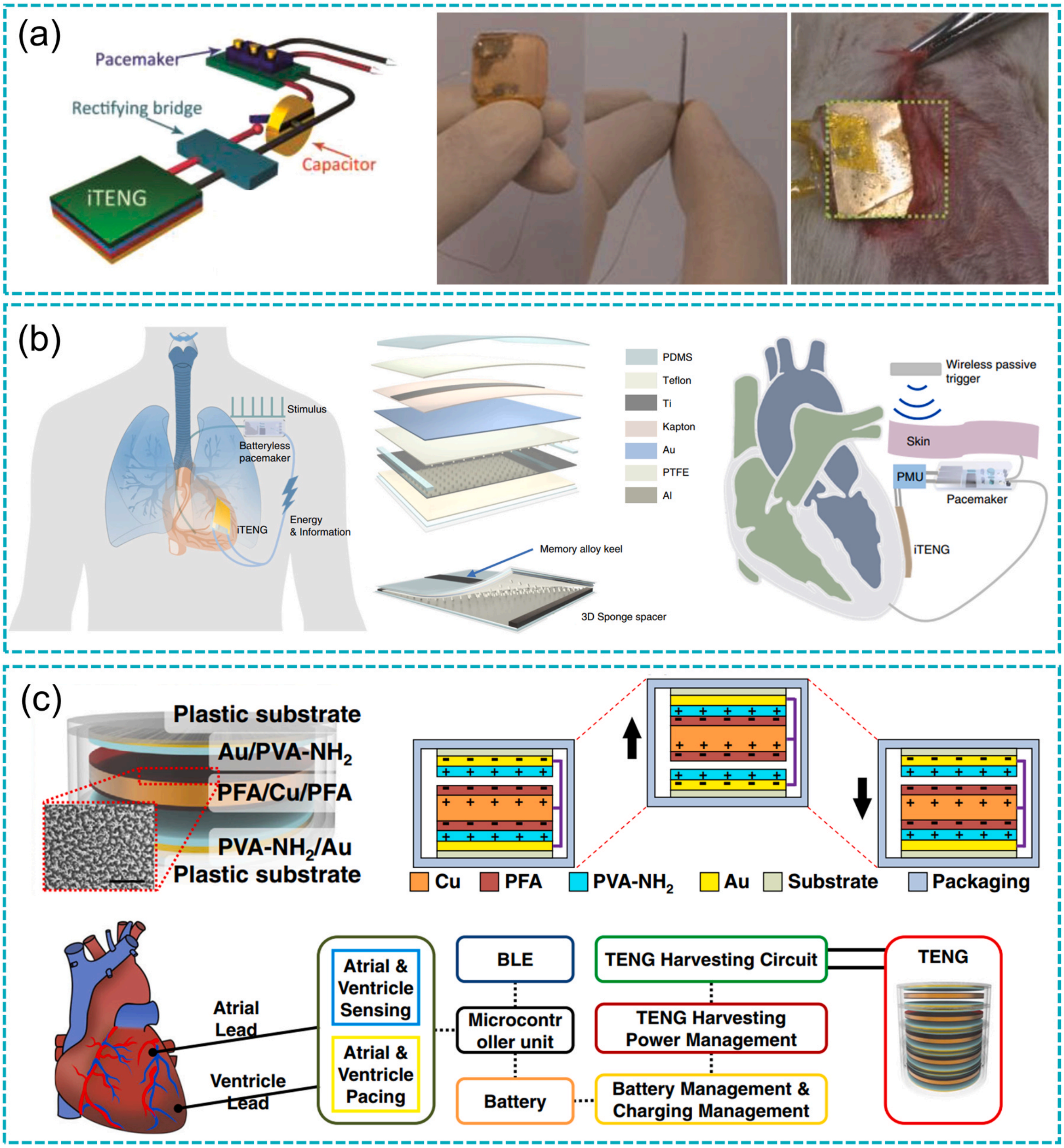

Fig. 6. (a) TENG-powered pacemaker. (b) Schematic diagram of the symbiotic pacemaker system. (c) Self-rechargeable cardiac pacemaker system with TENG. (a) Reproduced with permission [124]. Copyright 2014, Wiley-VCH. (b) Reproduced with permission [42]. Copyright 2019, Springer Nature. (c) Reproduced with permission [125]. Copyright 2021, Springer Nature.

5. TENG-based electrical stimulation therapy in health rehabilitation

5.1. Electrical stimulation of wound healing

Electrical stimulation can generate a uniform symmetrical electric field at the wound site and form an endogenous potential difference, thus enhancing the proliferation of keratinocyte-fibroblast and accelerating wound healing [130–133]. Jeong et al. reported a wearable electrical stimulation patch based on ionic TENG for accelerated wound healing [38]. The patch is constructed based on a stretchable gel-based platform, including TENG, wires, and multi-functional ionic patches (Fig. 7a). In the elastic microtubule structure, the ion conducting and stretchable organo-gels fibers are woven together like fabric, serving as both wearable TENG and stretchable wires. The energy harvested by the ionic TENG is transmitted to the multifunctional ion patch via stretchable ion wires, which creates an electric field at the wound area. The ion patch is encapsulated in an elastic film and used as both electrodes and wound dressing. The experimental results showed that the ion TENG patch significantly promoted the migration and proliferation of fibroblasts, as well as the secretion of biological factors related to cell activation in vitro wound healing.

Effective antimicrobial treatment helps to reduce the duration of the inflammatory period, avoid wound infection and accelerate the proliferation process [134,135]. Barman et al. developed a wearable self-powered wound excipient platform that can provide on-demand treatment for normal and infected wounds (Fig. 7b) [126]. The platform has a double-layer stacked construction, using two layers of carbon fiber fabric as the substrate and electrode layer. Thermocatalytic bismuth telluride nanosheets (Bi_2Te_3 NPs) modified on carbon fiber fabrics can generate H_2O_2 in situ through self-activation of the surrounding temperature difference, thus effectively inhibiting the growth of

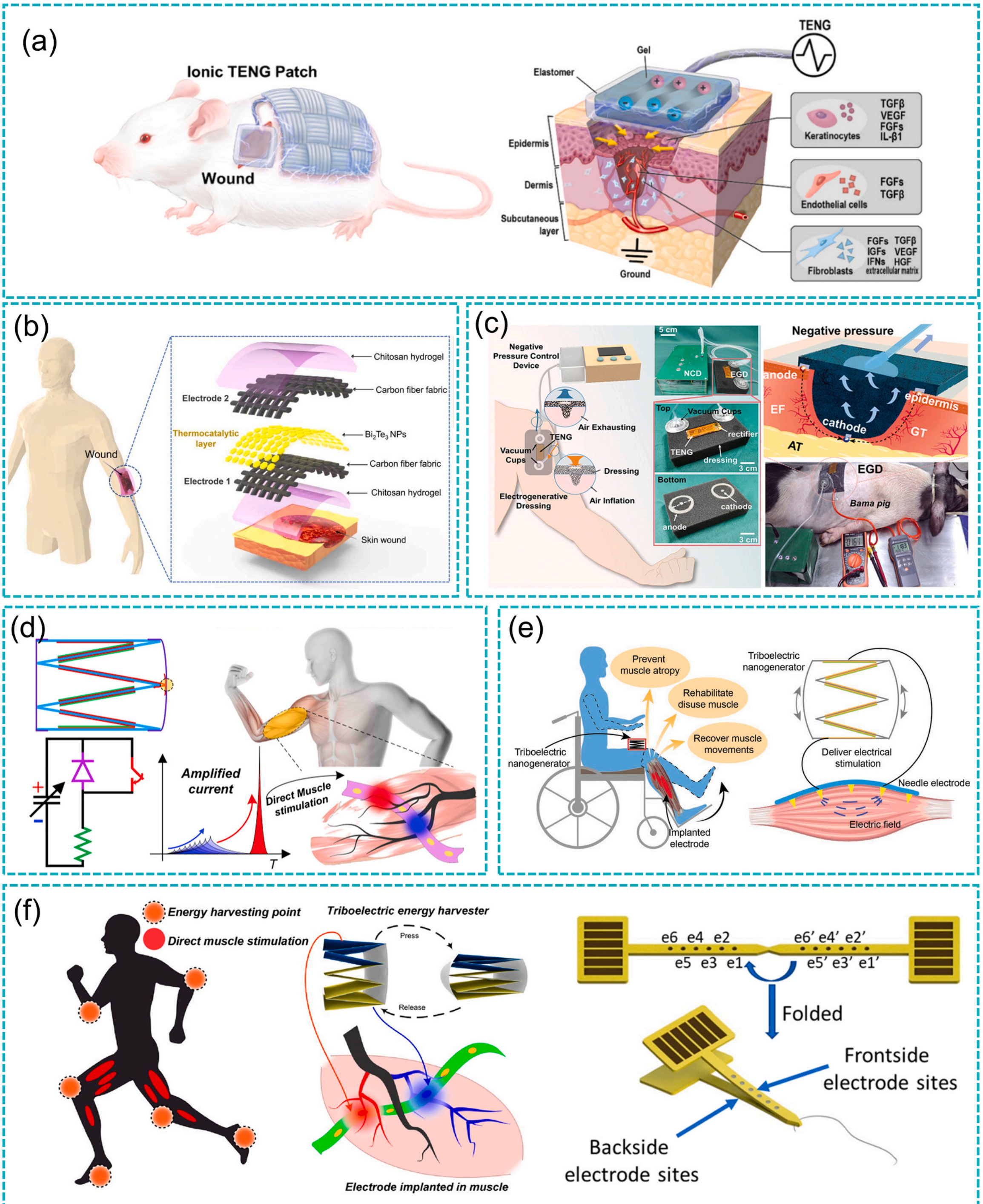

Fig. 7. (a) TENG assisted ion patch to accelerate wound healing. (b) Self-powered multifunctional dressing for accelerated wound healing. (c) An electro-generative dressing system to boost wound repair. (d) Direct muscle stimulation using diode-amplified TENG. (e) Electrical pulses generated by the TENG are used to stimulate muscles directly. (f) Self-powered direct muscle stimulation using a TENG integrated with a multiple-channel electrode. (a) Reproduced with permission [38]. Copyright 2021, Elsevier. (b) Reproduced with permission [126]. Copyright 2023, American Association for the Advancement of Science. (c) Reproduced with permission [127]. Copyright 2023, Wiley-VCH. (d) Reproduced with permission [128]. Copyright 2019, Elsevier. (e) Reproduced with permission [39]. Copyright 2019, Wiley-VCH. (f) Reproduced with permission [129]. Copyright 2019, American Chemical Society.

bacteria at the wound site. The H_2O_2 generated by the dressing is easily controlled by manipulating the treatment time, so the antibacterial activity can be easily adjusted according to the severity of the wound infection. At the same time, the dressing electrode is connected to the arched TENG, through which electrical stimulation is provided to enhance cell proliferation, migration and angiogenesis, accelerating wound healing.

Negative pressure wound treatment (NPWT) can create a favorable proliferative microenvironment for wound re-epithelialization by continuously removing necrotic tissue or infected material [136,137]. Luo et al. developed an electrogenerated regenerative dressing by combining TENG and NPWT (Fig. 7c) [127]. NPWT timing controls the pressure changes inside the dressing, driving the integrated TENG to convert the mechanical deformation induced by negative pressure into electrical energy, forming a compensating electric field, and stimulating wound repair. Large animal experiments have shown that electro-regenerative dressing can reshape the wound field weakened by NPWT, guide epithelial migration and accelerate re-epithelialization of proliferation by promoting early transformation of inflammation/proliferation, and promote wound healing.

5.2. Electrical stimulation of muscle

Neurological disease or nerve injury can lead to loss of control of an otherwise intact neuromuscular system, loss of muscle function, and significantly reduced quality of life for patients [138]. When muscles lose nerve drive, they quickly atrophy. Muscle electrical stimulation can effectively prevent or reverse muscle atrophy, and restore meaningful muscle movement [33,139]. Wang et al. proposed a diode amplification TENG for direct muscle stimulation (Fig. 7d) [128]. The TENG adopts a zig-zag shape stacked structure and consists of 11 layers of Al-PTFE triboelectric pairs in parallel. The diode can accumulate the charges generated by the various layers of the TENG and release them together in a very short time to achieve a short and large current pulse. The TENG is connected to the tibialis anterior muscle of the rats via a neural interface, which stimulates the rats to kick their feet forward. Six electrode pads on the neural interface can be formed into different electrode pairs for stimulation. The experimental results show that almost all the combinations can be successfully stimulated when the diode amplifies the current. However, when the current is not amplified by the diode, the stimulation can be successful only when the electrode is very close to the motoneuron.

The low current generated by the TENG can also be used directly for muscle electrical stimulation. Wang et al. presented a low-current direct muscle stimulator for rehabilitation treatment based on a TENG and a multiple-channel spiked electrode (Fig. 7e) [39]. The TENG also uses a zig-zag shape stacked structure, Al and PTFE as the triboelectric pairs. The spiked electrode consists of five channels and is prepared using microelectromechanical technology. The experimental results of tibialis anterior muscle stimulation in rats indicate that changing the electrode configuration at different spatial positions can achieve the optimal stimulation efficiency of TENG. Compared with traditional electrical

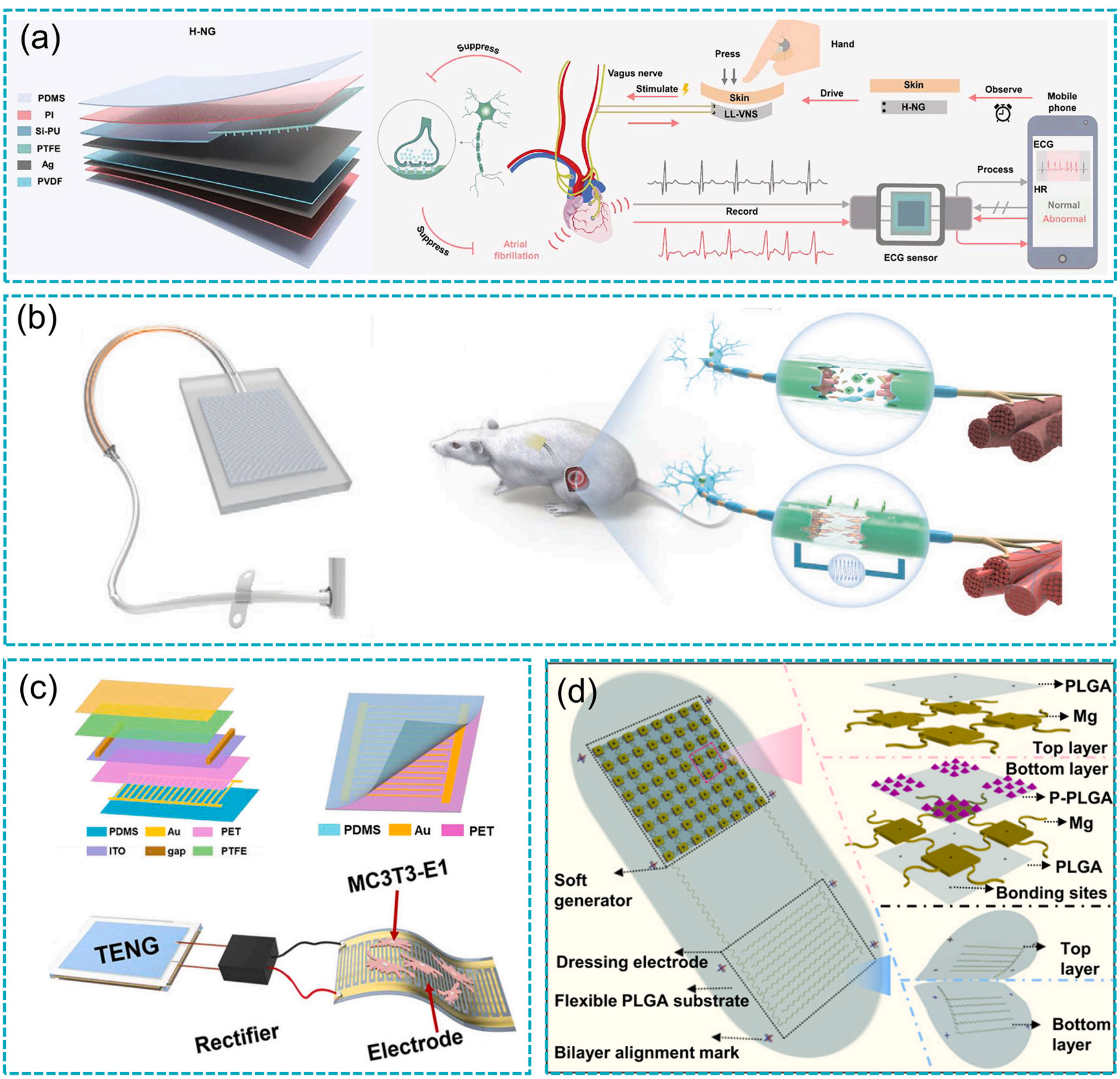

Fig. 8. (a) Self-powered low-level vagus nerve stimulation system for atrial fibrillation treatment. (b) TENG-based neural interfacing for effective sciatic nerve restoration. (c) Self-powered implantable electrical stimulator for osteoblasts' proliferation and differentiation. (d) Self-powered implantable and ultra-flexible bone fracture electrical stimulation device. (a). Reproduced with permission [40]. Copyright 2022, Elsevier. (b) Reproduced with permission [141]. Copyright 2022, Wiley-VCH. (c) Reproduced with permission [142]. Copyright 2019, Elsevier. (d) Reproduced with permission [41]. Copyright 2021, Proceedings of the National Academy of Sciences of the United States of America.

stimulation methods, TENG-based muscle electrical stimulation is more stable. This may be due to the output characteristics of the TENG with long pulse width and low current amplitude. Another work of this author also used zig-zag shape stacked TENG and multi-channel electrodes to explore the parameters that control the efficiency of muscle stimulation (electrode-motoneuron position and waveform polarity), providing a reference for the application of TENG in muscle electrical stimulation (Fig. 7f) [129].

5.3. Electrical stimulation of nerve

Electrical nerve stimulation is the use of electrical signals with a certain waveform, amplitude, frequency, and polarity to stimulate nerve tissue and regulate the activity of the nervous system, thereby improving the pathological state of patients and achieving therapeutic effects. The stimulation electrode is physically connected with adjacent Nervous tissue in the form of cuffs or probes. Electrical nerve stimulation is widely used in the regulation and treatment of neurological diseases, neuropsychiatric diseases, acute/chronic pain, organ dysfunction and movement disorders [28,140]. Low-level vagus nerve stimulation (LL-VNS) is a promising method for the treatment of atrial fibrillation. Sun et al. designed a closed-loop self-powered LL-VNS system based on a hybrid nanogenerator (H-NG) for the routine treatment of atrial fibrillation patients [40]. The system mainly consists of three parts: sensing, information processing and electrical stimulation therapy (Fig. 8a). The sensor module uses piezoelectric nanogenerators (PENG) as sensors to extract pulse waves from the skin and relies on a mobile phone and app to transmit and process the data. The H-NG is the core component of the electrical stimulation therapy module, which is composed of PENG and TENG. The piezoelectric material is polarized PVDF. Silver electrode and polarized PTFE are served as triboelectric materials for TENG. According to the warning information of the mobile phone, the user can tap the H-NG electrical stimulator to exert its anti-cholinergic effect by inhibiting the activity of the vagus nerve, so as to prevent atrial fibrillation and achieve the therapeutic effect. In vivo experiments in rats show that LL-VNS can produce 5–15 μA of peak current, which directly acts on the vagus nerve, greatly shortening the duration of atrial fibrillation, thus alleviating the symptoms of atrial fibrillation.

Electrical stimulation can promote the regeneration of axons for the repair of nerve damage. Zhou et al. reported an implantable self-regulated neural electrical stimulation system (ISR-NES) composed of TENG and a nerve cuff electrode for sciatic nerve repair (Fig. 8b) [141]. The system uses external stimulation to mimic the natural electrical impulses of human nerves and directs the stimulation signals through the neurons to the damaged sciatic nerve site. The TENG adopts a contact separation working mode, driven by respiratory movements and routine activities. The voltage signal generated by the TENG directly acts on the injured nerve through the nerve sleeve electrode to promote its recovery. Four weeks of animal experiments shown that the ISR-NES system can accelerate axon growth by accumulating the growth-associated protein (GAP43) at the site of sciatic neuropathy.

5.4. Electrical stimulation of osteogenesis

Bone has the functions of exercising, supporting, and protecting the body, undertaking and completing daily loads and physiological activities [143–145]. Promoting the proliferation and differentiation of osteoblasts is the key to maintaining bone homeostasis in the treatment of osteoporosis and fracture healing [146]. Tian et al. developed implantable self-powered electrical stimulator for enhancing osteoblast function [142]. The stimulator consists of a TENG, a rectifier bridge, and a flexible interdigital electrode (Fig. 8c). TENG adopts a contact separation working mode, with Al and PTFE thin films as triboelectric layers. The interdigital electrode uses PET as the substrate, and the entire device is packaged by 50 μm thick PDMS. MC3T3-E1 was selected as the model cell for electrical stimulation experiments, and the results showed that the intracellular Ca^{2+} level was upregulated after electrical stimulation. This self-powered electrical stimulator can significantly promote the attachment, proliferation, and differentiation of osteoblasts. After 3 days of stimulation, the proliferation rate of MC3T3-E1 increased by 23.82 %, and after 12 days of stimulation, the cell differentiation rate increased by 28.2 %.

Yao et al. reported a self-powered ultra-flexible and bioabsorbable fracture electrical stimulation device (FED) [41]. The entire device is constructed based on biodegradable PLGA material, consisting of a TENG for generating electrical pulses and a pair of interleaved dressing electrodes that provide electric fields (Fig. 8d). FED can adhere tightly to the surface of irregular tissue and generate electrical stimulation signals only from the associated body movements, providing closed-loop biofeedback therapy for rapid healing of fractures. The TENG uses an island-bridge electrode and a pyramidal microarray structure for excellent flexibility and considerable electrical output. In vivo experiments in rats shown that tibial fractures achieve effective healing within 6 weeks under FED treatment, while the control group takes more than 10 weeks to achieve the same healing effect. Moreover, compared with the control group, the bone mineral density and flexural strength increased by 27 % and 83 %, respectively. Mechanism studies shown that the electric field generated by FED can activate related growth factors to regulate bone microenvironment and promote bone regeneration, maturation and mineralization. Notably, in an implanted environment, the device rapidly degrades and reabsorbs within 14 weeks without the need for invasive surgical removal.

6. Conclusion and perspective

In this review, the research progress of TENG in health rehabilitation is introduced from the three main functions: self-powered sensors, integrated systems and bioelectrical stimulation. First, due to its unique mechano-electric conversion characteristics, TENG can output different electrical signals according to external stimuli without additional power. It can act as a self-powered sensor to monitor breathing, pulse, heart rate, body movement and other physiological information in real-time. In combination with wireless data transmission technology, the TENG can also be used as an implantable sensor to provide favorable data support for treatment optimization. Second, TENG is adept at harvesting low-frequency mechanical energy and has unique advantages in the construction of self-powered wearable or implantable devices. By integrating with other sensors or chips, a hybrid system can be formed to achieve more functions. Third, TENG has high biosafety for human body on account of its output characteristics of high voltage and low current. The electricity generated by TENG can be directly used to stimulate cells, tissues, or organs for the therapeutic and rehabilitation. Table 2 summarizes the typical cases and application characteristics of TENG in health rehabilitation. In addition to the rehabilitation of common diseases, TENG based self-powered devices provide innovative methods for precise cancer treatment. TENG can drive various micro/nano actuators to achieve targeted drug therapy, photodynamic therapy, and electric field therapy in tumor areas, reducing damage to normal cells [147–150]. Overall, the advancement of TENG-based health rehabilitation technology has greatly promoted the development of personalized healthcare and mobile therapy. We believe that the continuous integration of TENG with the Internet of Things, cloud computing, artificial intelligence and other technologies will inject new vitality into the development of self-powered medical electronic devices, enabling self-powered medical electronic devices to achieve more complex and precise functions.

Even though great progress has been made in the application of TENG in health rehabilitation, there are still some challenges should be carried out for future development:

(1) In a self-powered system, whether as a power source or an active sensor, energy density is a key parameter that determines the

Table 2
Summary of the characteristic and property of TENG applied in health rehabilitation.

Function	Structure	Working Mode	Triboelectric Materials	Electrical Output	Ref.
Sensor	Nanofiber	C-S[a]	Au/PAN & PA66/Au	420 V, 1.8–9.5 μA	[72]
Sensor	Floating rotary	F-T[b]	PTFE & Nylon	~17 V, ~28 μA	[34]
Sensor	Spacer structure	C-S	Cu/FEP & PA/Cu	15 V, 75 nA	[73]
Sensor	Self-arched	C-S	Al & Ecoflex	6.5 V, 175 nA	[74]
Sensor	Textile	C-S	Nylon & Conductive yarn	11 V, ~9 nA	[35]
Sensor	Spacer structure	C-S	Mg/PLA/C & Mg/PLA/C	4.2 V	[85]
Sensor	Radial grating	F-T	Cu & Kapton	~75 V, ~1.2 μA	[36]
Sensor	Grating	F-T	Cu & PI	10 V	[86]
Sensor	Grating	F-T	Cu & Kapton	~40 V	[87]
Sensor	Textile	C-S	Ag-PE fiber & Conductive fabric	~0.75 V, ~3 nA	[37]
Power supply	Grating	F-T	PTFE & Cu	~240 V, 8.39 μA,	[102]
Power supply	Grating	F-T	PTFE & Nylon	~60 V, ~4 μA	[44]
Power supply	Radial grating	F-T	PTFE & Cu	250 V	[43]
High voltage	Radial grating	H-S[c]	Nylon & Kapton	20 kV	[103]
Stimulator	Spacer structure	F-T	PI & PTFE	20 V, 1 μA	[104]
Power supply	Spacer structure	C-S	PDMS & Al	12 V, 0.25 μA	[124]
Power supply	Spacer structure	C-S	PTFE & Al	93 V, 9 μA	[42]
Power supply	Five-stacked	C-S	$PVA\text{-}NH_2$ & PFA	136 V, 2 $\mu A/cm^3$	[125]
Stimulator	Fabric	C-S	Organogel/ Sllicone & Al	75 V, 3.6 μA	[38]
Stimulator	Double-layer stacked	C-S	PTFE & Al	25 V, 1 μA	[126]
Stimulator	Spacer structure	C-S	PTFE & Al	4.7 V, 100 nA	[127]
Stimulator	Zig-zag shaped	C-S	PTFE & Al	~30 V, ~40 μA	[128]
Stimulator	Zig-zag shaped	C-S	PTFE & Al	~50 V, 75 μA	[39]
Stimulator	Zig-zag shaped	C-S	PTFE & Al	47 V, 35 μA	[129]
Stimulator	Spacer structure	C-S	PTFE & Ag	/	[40]
Stimulator	Spacer structure	C-S	PDMS & PA6	~11.5 V, ~0.15 μA	[141]
Stimulator	Spacer structure	C-S	PTFE & Al	100 V, 1.5 μA	[142]
Stimulator	Spacer structure	C-S	PLGA & Mg	0.5–6.8 V	[41]

[a] C-S: contact-separation mode.
[b] F-T: freestanding triboelectric-layer mode.
[c] H-S: horizontal-sliding mode.

continuous and stable operation of the entire system. At present, the power consumption of most wearable and implantable medical electronic devices is above milliwatts, much higher than the output power of TENG. Therefore, there is an urgent need to enhance electrical energy output and energy conversion efficiency by creating micro/nanostructures, chemically modifying frictional surfaces, developing new materials, and designing innovative structures. In addition, a rationally designed energy management module can effectively store and manage the energy harvested by TENG, minimize the waste of electrical energy and increase the output power of the system.

(2) The stability of the TENG needs to be further improved to avoid degradation of device performance during long-term operation. Since the TENG generates charge through the friction, bending and stretching of two triboelectric layers, material wear, deformation and fatigue of the triboelectric layers are inevitable. Developing new materials that are more wear-resistant or have self-healing capabilities would be an effective solution. Moreover, the output stability of TENG may be affected by temperature and humidity, especially in enclosed environments within the body. Therefore, it is necessary to develop waterproof/hydrophobic materials, self-cleaning materials and new packaging methods.

(3) Applying the TENG to personalized medicine will also require a significant investment in multi-functional integrated sensors and artificial intelligence, combining machine learning and remote control. Efforts need to be made to develop machine learning algorithms to process, analyze, and identify node data and incomplete information from various sensors, and adjust health management solutions through artificial intelligence analysis.

(4) Electric stimulation therapy requires stable, precise, and highly controllable stimulation signals. TENG often generates irregular and uncontrollable signals in response to organ or human motion, which not only affect the effectiveness of electrical stimulation therapy, but may also have potential impacts on surrounding tissues or organs. By integrating energy storage units and pulse generators to form a hybrid system, it will be an effective solution to achieve stable and controllable stimulation.

(5) For implantable devices, the structural design of TENG should be further miniaturized and functional integration. According to the size of the tissue or organ, the healthcare device should be highly integrated and miniaturized to match the implantation site of the tissue or organ, achieving monitoring, information feedback, and treatment while reducing infection, injury, and their impact on the daily lives of patients. At the same time, lightweight, inherently flexible and stretchable materials and good biocompatibility should be used to construct implantable devices, so that they can be stable and closely in contact with human tissues or organs, and effectively avoid adverse immune reactions during chronic implantation. In addition, efforts are needed in the field of biodegradable or bioabsorbable materials to avoid financial and physical pain for patients with secondary surgeries.

(6) At present, biological experiments mostly use small animals such as rats or rabbits, and their biological effects may differ from those of humans in terms of mechanism and performance. Therefore, more clinical research needs to be shifted to humans or larger animals that are more similar to humans.

With further research on these key challenges in mechanism research, material development, mechanism design, system integration, etc., TENG will receive more widespread attention in the field of health rehabilitation. We sincerely hope that this review will promote the development of TENG in the field of health rehabilitation and provide some important research directions for new researchers.

CRediT authorship contribution statement

Yansong Gai: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yonggang Jiang:** Supervision, Resources, Writing – review & editing. **Zhou Li:** Conceptualization, Supervision, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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