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Making use of nanoenergy from human – Nanogenerator and self-powered sensor enabled sustainable wireless IoT sensory systems

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ABSTRACT

Nowadays, the human body is gradually digitized by various wearable and implantable electronics. The establishment of a sustainable wireless internet of thing (IoT) sensory system is urged by developing the energy harvesters and self-powered sensors based on specific scenarios. As one of the dominant energy sources from the human body, mechanical energy offers a great opportunity for piezoelectric nanogenerator (PENG) and triboelectric nanogenerator (TENG) to accomplish the tasks. Both two techniques are featured with simple conversion mechanisms and easy integration for wearable and implantable devices. In this review, starting from the fundamental principle, both wearable and implantable PENG and TENG are thoroughly discussed, with different mechanical stimuli, including force, strain, vibration, *etc*., and various materials, such as ceramic, polymer, textile/nanowires, *etc*. Furthermore, based on the outputs from PENG and TENG, the self-powered physical sensors are investigated to exploit the potential of motion recognition or physiological signals monitoring. Besides, the introduction of hybrid systems also provides an overview of the joint function of PENG and TENG for enhancing both power generation and sensing performances. For achieving the IoT sensory network, the representative researches on wireless transmission of both energy and sensing signals are investigated according to the different transmission ranges. In general, this review offers comprehensive knowledge about the recent advances and the future outlook regarding the sustainable wireless sensory system specifically for the human body.

Contents

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Introduction

For decades, miniaturization of electronics and advances of materials are paving the way for the prosperous development of wearable and implantable devices. Human is experiencing the great conveniences which are brought by diverse electronics, including smartwatch, glasses, shoes, glove, pacemaker, and necklace, *etc.* With the aid of 5 G communication technology, artificial intelligence (AI), and edge computing, the highly digitized human will undergo a seamless involvement in the whole network or internet of things (IoT) [1]. Diversified applications are realized through the vast amount of distributed devices, such as healthcare, environment monitoring, traffic control, and factory automation [2–6]. Specifically, the IoT sensory system usually consists of several key components, i.e., physical and chemical sensors [7,8], power sources, processing and transmission units. Some of these systems possess the functions as the mobile console for processing and displaying the data. Meanwhile, various sensors with physical, optical or chemical mechanisms, form another significant group in wearable or implantable systems [9]. Hence, our physical activities, vital sign, physiobiochemical indicators can be continuously monitored for health inspection or performing the various manipulations in virtual spaces or robotic control. Besides, the environmental variations are also able to be detected for further utilization. Among the different research fields, wearable and implantable devices with healthcare and human machine interface (HMI) functions are drawing the great attention of the research groups [10], in order to realize the aforementioned IoT sensory system. However, the current commercialized devices, such as piezoresistive, optical, and capacitive sensors, and various actuators, usually rely on the battery-based power supply, which is inevitably encountered with some constraints, including the long-term sustainability and the further shrinkage of device size. Especially for implantable systems and the wireless applications, they are experiencing the grand challenges and unknown risks in replacing the battery.

As a solution to this urgent power issue, energy harvesters based on different operation principles are undergoing rapid development [11], since the human body is as a natural power source that is generating both mechanical and heat energy. Noticeably, the human motions are not only generating a considerable amount of mechanical energy, but also revealing the useful information via those motions, which can help to identify the sports activities, the disorders, and the impairments, *etc.* Therefore, it is necessary to develop the compact devices with both energy harvesting and tactile sensing functions for enabling the comfortable and user-friendly wearable/implantable systems. Driven by these concerns, there are two major technologies of transducer which are frequently reported, known as piezoelectric nanogenerator (PENG) and triboelectric nanogenerator (TENG), as both of them can directly convert the mechanical stimuli into the electrical output. These two mechanisms were originally developed as the pure energy harvesters ranging from wearables to blue energy [12], and the different output boosting strategies were introduces [13], such as frequency conversion for PENGs, and surface texturing for TENGs. The recent progresses indicate the diverse achievements in multi-dimensional physical and chemical sensing, actuation, neural interfaces, and photonics modulation, *etc.* [14,15]. All of these researches allow PENG and TENG to be incorporated into each part or stage in a complete IoT system for better sustainability and intelligence.

Specifically, these two mechanisms are showing the high feasibility of developing a self-sustained wearable and even implantable system [16–19]. Owing to high power density, PENGs can be integrated into smaller devices to supply power, such as a pacemaker. The introduction of polymer based piezoelectric materials also improves the flexibility of PENGs as wearable devices. For TENGs, due to the wide choices of available materials, as well as the highly customizable design, many reported research works illustrated high stretchability, biocompatibility, facile fabrication process, low cost, and large area deployment. In the meantime, both PENG and TENG are showing their own drawbacks, such as large area fabrication for PENGs, and low power density for TENGs, which require continuous study. As one of the solutions, the relevant researches on hybridized nanogenerator using PENG and TENG are also showing a promising future by leverage their own advantages as the complementary part of each other.

Furthermore, a better way to solve the energy crisis for wearable and implantable sensors is to fully utilize the respective effects used in nanogenerators to developing the diversified self-powered sensors [20]. Hence, PENGs and TENGs are vastly modified to perform the corresponding physical sensing functions [21], i.e., pressure [22], shear force [23,24], strain [25], vibration, acceleration and gyroscope, *etc.* Recently, researches of self-powered sensors are showing some tendencies. Firstly, there are major efforts to achieve the comparable sensitivity and sensing range against the commercialized product in specific applications, such as pulse measurement, and foot pressure detection [26]. In the meantime, the multi-functional sensors with the capability of detecting various external stimuli are frequently studied as well in order to mimic the functions of human skin, i.e., normal and shear force, temperature, and humidity, *etc.* [27]. Additionally, by adopting the functional coating or film, the electrical output from TENG and PENG can also be altered to be in response to the variation of the contacted medium, like sweat, blood, and body fluid. Therefore, various self-powered chemical sensors are also feasible by applying nanogenerators [7,28,29].

To fully implement the sensor node under the IoT concept, those self-powered sensors are frequently assembled with signal processing and transmission module to build a wireless sensory network [30–32]. Meanwhile, the solutions of conducting the wireless transmission with the power supply from nanogenerators for wearable devices are crucial to ensure the long-term operation without the bulky battery [3]. A typical way is to integrate an external circuit consists of a power management unit (PMU) and wireless transmission module, which can be entirely or partly supported by nanogenerators. Besides, the short-range transmission of the generated energy also can be achieved via the facile designed transmitters and collectors, such as coil-based resistor-capacitor-inductor (RLC) circuits. The wirelessly transmitted sensing signals from those nanogenerator-based self-powered sensors are characterized in terms of frequency shift and/or coupling intensity directly. Eventually, the sensing signals from those nanogenerator-based self-powered sensors are able to be delivered directly. All of these advances are indicating the promising directions of accomplishing the advanced wearable system for IoT.

In this review, as briefly illustrated in Fig. 1, we intend to present a comprehensive overview of the recent advances of PENG and TENG related researches on wearable technologies. Starting with the brief introduction of piezoelectric and triboelectric mechanisms and their typical examples, we firstly focus on the diverse designs of wearable PENG and TENG for harvesting the mechanical energy to supply the device operation. Then, the PENG and TENG based self-powered wearable sensors for multi-purpose and multi-dimensional detection are investigated thoroughly. Next, the implanted devices are also discussed in terms of medical purposes. Finally, to have an outlook about the future research trend, the studies on IoT sensor networks are evaluated to identify the potential of initializing a highly intelligent wearable system for humans.

Working principles

Piezoelectric effect

Piezoelectric effect was discovered by French physicists Jacques and Pierre Curie in 1880. It refers to the induction of an electric charge that accumulates in certain solid materials (crystals, certain ceramics, polymer, and biological matter such as bone, DNA and various proteins) in response to an applied mechanical strain/stress, and lead to the polarization of its electric dipole moment, as illustrated in Fig. 2a(i). It is a reversible process: materials with the piezoelectric effect also exhibit the reverse piezoelectric effect, the internal generation of a mechanical strain resulting from an applied electrical field. As shown in Fig. 2a(ii), according to the charge collection directions (in-plane or perpendicular to the plan), there are two main parameters: d_{33} and d_{31}, known as piezoelectric coefficients which determine the capability of the charge generation along a specific direction against the deformation direction. Piezoelectric effect is then frequently applied to several applications [33–35], such as the ultrasonic transmitters, nanogenerators, sensors, piezoelectric inkjet printer, microphones, micro speakers, *etc.* Specifically, it is the basis for a number of scientific instruments, such as atom force microscopy, or the time reference source in quartz watches, *etc.* The most frequently applied materials include lead zirconate titanate (PZT) [36], polyvinylidene fluoride (PVDF) [37,38], ZnO [39], and AlN, *etc.* Additionally, the polarization process is required to enable the piezoelectric effect by rearranging the randomly oriented domains through applied DC voltage.

Triboelectric effect

Triboelectric effect can be defined as a phenomenon that the opposite electrostatic charges are created on both surfaces of two materials with different electronegativities through physical contact to balance the surface potential, and thus, a potential drop will be generated on both surfaces after separation, and resulting the compensating charges accumulated on the electrodes of both materials. As a consequence, there will be current flowing through the external circuit in response to the physical interactions, and hence, TENG can be applied to realize the mechanical energy harvesting tasks for the electronics via a specific power management circuit. Generally, there are mainly four basic operation modes for triboelectric effects, namely contact-separation mode [40,41], contact-sliding mode [42], single electrode mode [43], and freestanding mode [44] to be responsible for either vertical or lateral motion, as shown in Fig. 2b. For the contact-separation mode and contact-sliding mode, both triboelectrification layers are connected. On the other hand, single electrode mode and freestanding mode only has one output electrode for either one of the triboelectrification layer. Owing to the above features, TENG based physical sensors are then extensively studied to achieve the sensing of pressure [45], strain [46], sliding [47,48], vibration [49–51], and inertial [52], *etc.* Triboelectric effect as a universal phenomenon for most of the materials, offers the ease of wide options [53]. In addition, choosing the materials with a greater difference in electronegativity and microstructure engineering for increasing the effective charge preservation area can efficiently enhance the triboelectric output [54]. Some typical candidates include polytetrafluoroethylene (PTFE) [55,56], fluorinated ethylene propylene (FEP) [49,57], polyethylene terephthalate (PET) [58], nitrile [59],

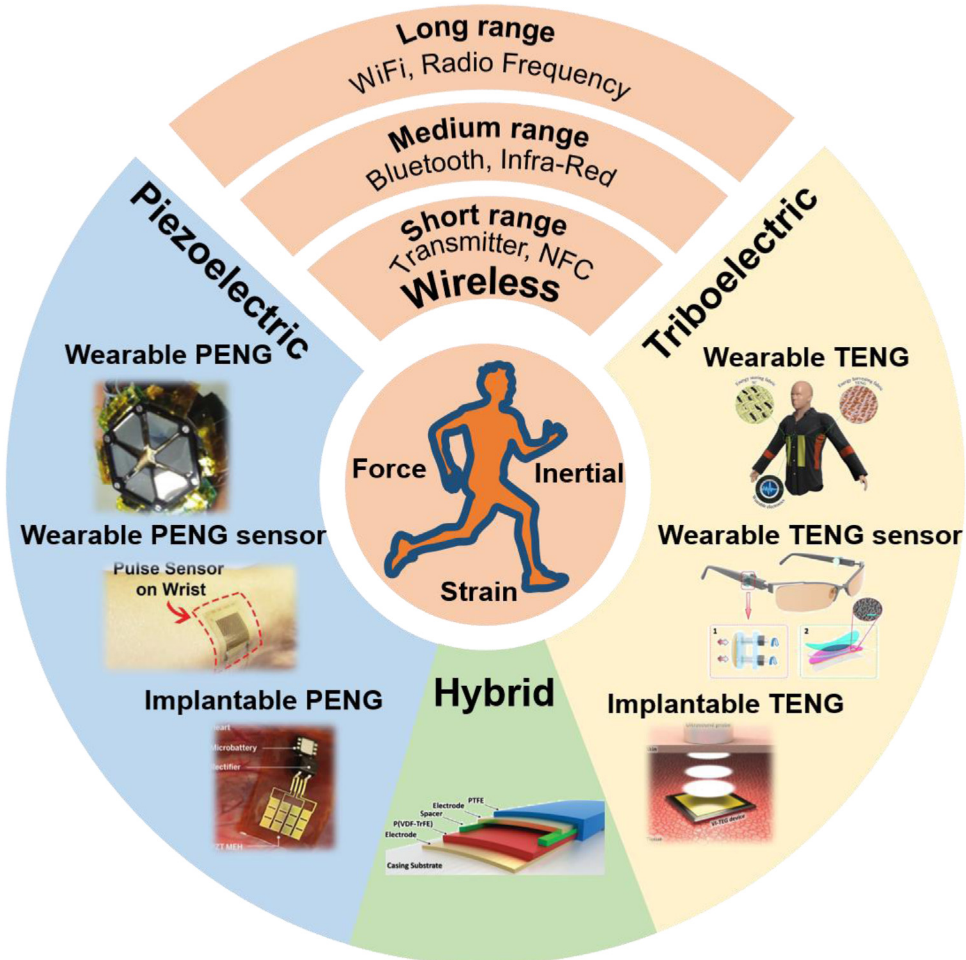

Fig. 1. Overview of PENG and TENG for wireless sensor applications. Printed with permission from Ref. [99], [212]. Copyright 2018, 2017 John Wiley & Sons. Ref. [156]. Copyright 2014 National Academy of Sciences. Ref. [133]. Copyright 2016, John Wiley & Sons. Ref. [259]. Copyright 2017, American Association for the Advancement of Science. Ref. [200]. Copyright 2019, American Association for the Advancement of Science. Ref. [310]. Copyright 2018, John Wiley & Sons.

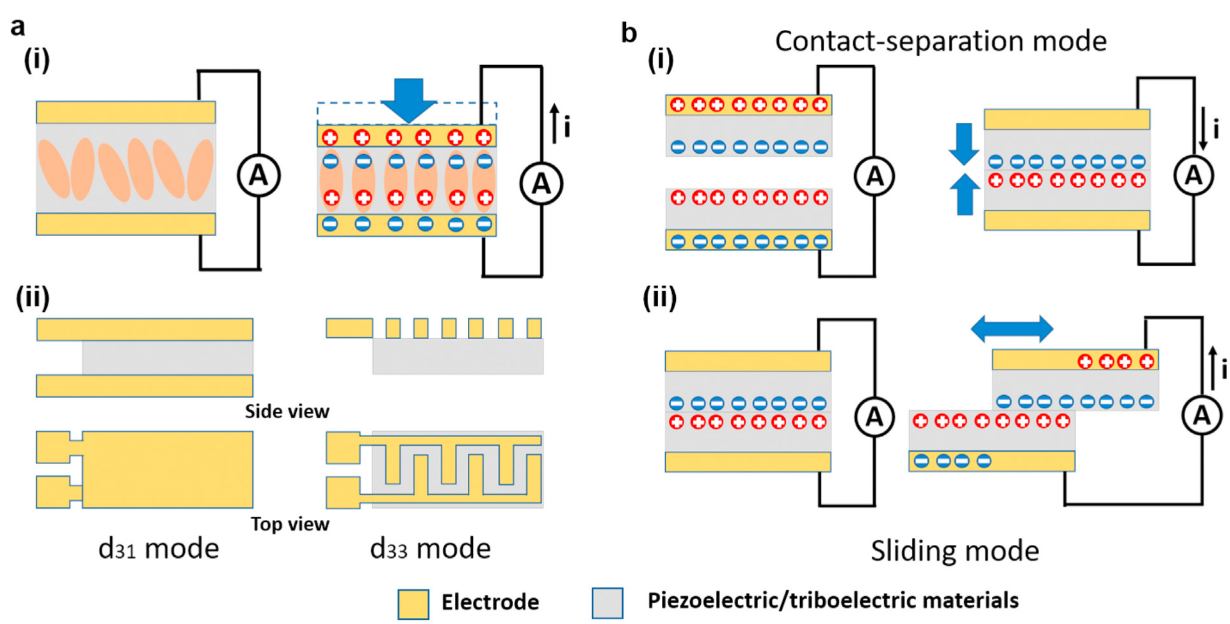

Fig. 2. Working principles of PENG and TENG.

silicone [60,61], polydimethylsiloxane (PDMS) [62,63], metals (Cu, Al, Ni *etc.*) [64–67], graphene [68], skin [69,70], water [71], *etc.*

Wearable nanogenerators

Wearable piezoelectric nanogenerators (PENGs)

Wearable PENG is developed rapidly due to its potential of the sustainable power supply with the emerging of wearable electronics, which is promising to get rid of the battery. Human body can generate a considerable amount of kinetic energy, such as hand motion [33,72–74], wrist motion [34,75–79], joint rotation [33,80–82], knee-joint motion [83–88], foot motion [35,89–93], clothes motion, motion of the backpack, and so on. Based on the development of micromachining technologies and piezoelectric materials, such as nanotechnology, MEMS process, piezoelectric thick film fabrication technology, flexible piezoelectric polymer film or fabric, wearable PENGs become more portable, and highly efficient. The recently reported PENGs based on these technologies, as shown in Fig. 3 have been investigated by using the kinetic energies in the human body.

Bulk ceramic film based wearable PENGs

For practical applications, the generated electrical energy will support the electronics with low power consumption. MEMS-based nanogenerators can provide a relatively high power density with a small volume. However, this power is still not sufficient to meet the requirement of many commercial devices. The process of piezoelectric thick film is the earliest approach that is developed for PENGs. As a result, the majority of PENGs are integrated into the existed wearable objects, such as clothes, glove, shoes, or others. So far, the PENGs of foot motion energy harvesting have been investigated as the most promising approach. As shown in Fig. 3a, the PENG was firstly presented by using a PVDF stave placing at the ball of the foot and a PZT Thunder at the heel [35]. The average net energy transfers of roughly 1 mJ/step for the PVDF and 2 mJ/step for the PZT Thunder. To further enhance energy conversion efficiency, a PVDF harvester based on a specially designed wavy structure provides an average output power of 1 mW during a walk at a frequency of 1 Hz [89]. The wavy structure can increase the effective area for the strain of the piezoelectric film. Recently, a heel harvester (Fig. 3b) was presented by utilizing the lever mechanism to gain maximum deformation of multilayer piezoelectric patches [91]. It takes full advantage of the user's weight, and amplifies footstep displacement and performs an average effective output power of 6.13 mW under a harmonic excitation of 2.3 Hz. Additionally, Qian et al. developed a sandwiched force amplification frame to transmit and amplify the vertical heel-strike force to the inner piezoelectric stack deployed in the horizontal direction [92]. The footwear harvester with six stacks performs 9 mW/shoe average output power at the walking speeds of 4.8 km/h.

Besides, the backpack is an existed wearable object carried by a strap on the back. Human motion can induce its oscillation due to the inertial. As a result, a PENG based on a piezoelectric cantilever was investigated by Chen et al. for harvesting kinetic energy from a backpack [94]. When the walking speed is 2−6 km/h, the amplitude of the acceleration is around 0.7–2.2 g for the accelerator placed on the horizontal frame, and the vibration level is higher in the frequency range of 2–12.7 Hz. The harvester can achieve a power output of 43.64 μW with a single piezoelectric element at the speed 4 km/h. In addition to foot movements, knee-joint motion is another promising energy resource for wearable PENGs. The device (Fig. 3c) relies on the plucking technique to achieve frequency up-conversion [83]. The average power output of the prototype, featuring four PZT-5H bimorphs, was 2.06 ± 0.3 mW [84,85,87]. For further optimization, contactless magnetic plucking was presented by Pozzi et al. Record levels of rectified electrical power of over 50 and 70 mW per walking and running steps, respectively, were obtained [86]. Furthermore, as the walking speed increased from 3 to 7 km/h, the power output of a magnetically plucked wearable knee-joint PENG can increase from 1.9 ± 0.12 to 4.5 ± 0.35 mW, which was sufficient for powering a wireless sensing system [88]. A comparison of the reported PENGs utilizing the excitations from walking or running is summarized in Table 1.

The development of high-performance piezoelectric ceramics for flexible PENGs is an effective approach to enhancing the wearability. A flexible PENG (Fig. 3d) based on PZT material with a total thickness of 170 μm is utilized, which provides sufficient flexibility for attachment on clothes or human skin. The harvester generated an open-circuit voltage of 165 V and a short-circuit current of 1.5 μA through mechanical bending motion on a linear stage [95]. Li et al. proposed a wearable energy harvester with a micro-electroplated ferromagnetic nickel cantilever based on the magnetic interaction between the magnetized cantilever and a magnet on the substrate (Fig. 3e). Within one stretching/rebounding movement cycle, the generated electric energy is stable in the approximate range of 0.56–0.69 μJ for the whole frequency range of 0.5–5.0 Hz [96].

Watch-like PENGs based on the piezoelectric thick films have been proposed to harvest the kinetic energy of the wrist motion [34,75–79]. With the wrist motion, an eccentric proof mass embedded in the watch-like harvesters induces free vibration of the piezoelectric structure (Fig. 3f). This design with a frequency up-conversion function is widely adopted to scavenge low-frequency vibrational energy [34]. Given the lack of electricity generation at rest, an external excitation approach using a magnetic reluctance coupling was presented for the watch-like rotational PENG [75]. With this strategy, a battery can be charged during prolonged periods of inactivity. Lastly, the PENG with a functional volume of 1.85 cm^3 can generate 100 μW power at the optimal driving frequency is 25 Hz [75]. A similar PENG can generate about 100 μJ to 250 μJ under different hand movements [79]. The harvested energy from 30 min of jogging can supply the tracker up to 37 sampling cycles. Portable handheld PENGs are driven by hand motions [72–74]. Therefore, the excitation conditions are featured with low frequency, large acceleration, and unabiding. Fig. 3g depicts a flexible PENG employing a metal ball to impact on two sidewalls, which act as the bases of two piezoelectric cantilevers [72,73]. Each impact causes the free vibration of the piezoelectric cantilevers and offers the frequency up-conversion. The fabricated PENG can generate a maximum average power of 175 μW at the frequency of 4.96 Hz and an acceleration of 2 g.

Deposited ceramic film based wearable PENGs

Piezoelectric thin film deposition processes are mainly used to develop the microscale PENGs. MEMS-based PENG is a promising solution for wearable applications due to its small volume. Fig.4a illustrates a MEMS-based PENG with the broadband operation frequency and the capability of converting the random and low-frequency vibrations into the high-frequency self-oscillations. The peak power density can reach 159.4 W/cm^3 with a frequency of 25 Hz and an acceleration of 0.8 g [36]. However, this operation frequency of peak power density is still high for wearable applications. Thus, the rotational motion is applied to realize the frequency up-conversion function. Fig. 4b shows a wearable piezoelectric on-body harvesting system based on this approach. The piezoelectric cantilevers are directly connected to the rotating mass via a set of pins located near its rotational center for coupling effect. The energy produced by each pluck of a cantilever is 545 nJ, corresponding to a maximum output power of 11 μW for continuous plucking [97]. In a flexible MEMS, Han et al. developed a complex three-dimensional PENG, which has multiple operation modes under a

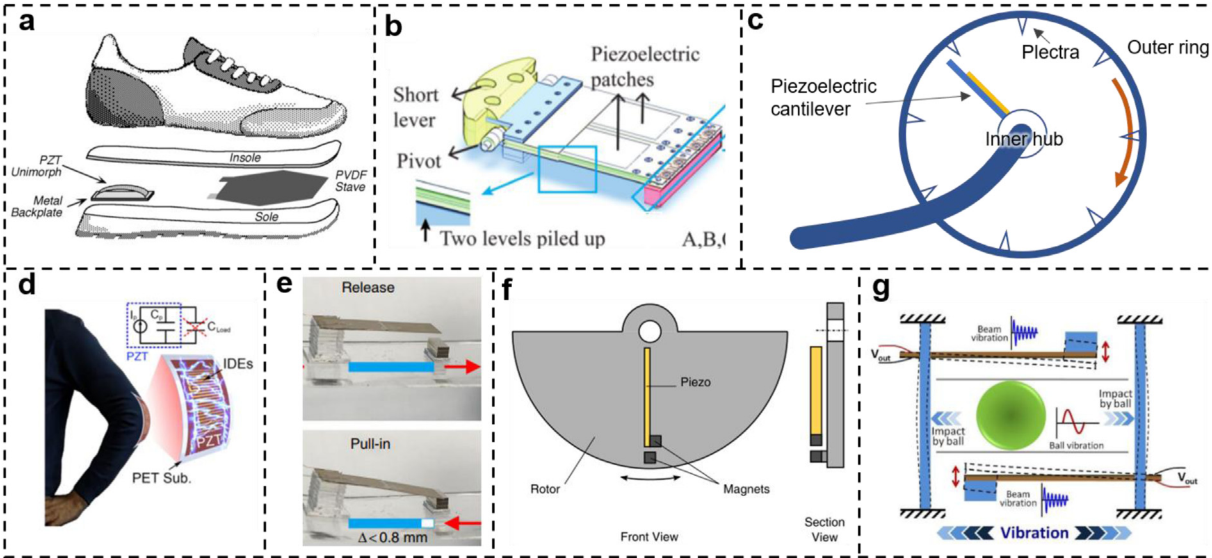

Fig. 3. Bulk piezoelectric ceramic film based wearable PENGs. (a) Parasitic power harvesting in shoes. Printed with permission from Ref. [35]. Copyright 1998 IEEE. (b) A nonlinear interface integrated lever mechanism enhanced footstep PENG. Printed with permission from Ref. [91]. Copyright 2018 American Institute of Physics. (c) Knee-joint energy harvesting based on plucking effect. (d) Energy extraction enhancement circuit improved flexible PENG. Printed with permission from Ref. [95]. Copyright 2019 Elsevier. (e) A wearable energy harvester for low-frequency human limb movement. Printed with permission from Ref. [96]. Copyright 2018 Springer Nature Limited. (f) A wearable piezoelectric rotational energy harvester. Printed with permission from Ref. [34]. Copyright 2013 IEEE. (g) A handy motion driven, frequency up-converting PENG [72,73]. Printed with permission from Ref. [73]. Copyright 2018 Springer-Verlag GmbH Germany, part of Springer Nature.

Table 1
Performance comparison of the reported PENGs under the walking or running.

Ref.	Materials	Volume of piezoelectric materials	Harvesting Mode	Excitation	Output average Power
[83]	PZT	$31.8 \times 12.7 \times 0.25$ mm^3	d_{31}	Single plucking action	2 μJ
[84,85,87]	PZT	$31.8 \times 12.7 \times 0.25 \times 4$ mm^3	d_{31}	Walking	2.06 ± 0.3 mW
[86]	PZT	$27 \times 6.5 \times 0.25 \times 16$ mm^3	d_{31}	Walking	50 mW/walking step 70mW/running step
[88]	PZT	$31.8 \times 12.7 \times 0.25 \times 4$ mm^3	d_{31}	Walking from 3 to 7 km/h	1.9 ± 0.12 to 4.5 ± 0.35 mW
[35]	PVDF + PZT	PVDF:65×44.8 mm^3 PZT: 25×38.1 mm^3	d_{31}	Walking	1 mJ/step [PVDF] 2 mJ/step [PZT]
[89]	PVDF	40×0.3 mm^3	d_{31}	Walking	1 mJ/step
[90]	PZT	$76.2 \times 31.75 \times 2.28$ mm^3	d_{31}	Walking	11.55 μJ/step
[91]	PZT	$46 \times 20.8 \times 0.3048$ mm^3	d_{31}	Walking	2.67 mJ/step
[92]	PZT	$49 \times 30 \times 6$ mm^3	d_{33}	Walking	9 mW/shoe

controlled, nonlinear buckling process (Fig. 4c). This device can provide root-mean-square voltages ranging from 2 mV to 790 mV [98]. The harvested energy is still insufficient to drive commercial electronics by comparing with the requirement of microelectronic chips or devices. The piezoelectric film deposition processes are suitable for fabricating hundreds of nanometers thick film with high piezoelectric performance. A strongly (001) oriented bimorph PZT film on metal foils grown by sputtering was used for wrist-worn PENG as shown in Fig. 4d [99]. This fabrication process can be controlled to achieve a thickness of 3 μm. A total of six beams can produce an output of 1.2 mW at 0.15 g acceleration, which is promising for practical applications.

Polymer film based wearable PENGs

Wearable PENGs for the joints generally have some common features, such as flexibility and conformability. However, the development of the flexible piezoelectric ceramics, piezoelectric co-polymer, or other composites for a breakthrough to the piezoelectric coupling coefficient is urgent. More innovative designs or advanced fabrication technologies are necessary to be employed for improving the insufficient output power to meet the power consumption of the commercial wearable electronics. Given the joint rotation is a large deformation motion, flexible piezoelectric materials are preferred to be used in the investigation of the wearable PENG, such as piezoelectric polymer films. For instance, a reported pure PVDF based PENG was placed on the back of the knee through an elastic cotton leotard. This PENG can obtain an output power of 1.45 μW during walking [80]. To improve the output power, Yang et al. presented a flexible PENG (Fig. 5a) that consists of a PVDF film attached to a curved substrate in a shell for harvesting energy from human motion [81]. The fabric worn on the elbow joints and fingers can generate an output power of 0.21 mW despite slow and irregular motions. For conformal wearing, a bionic single-electronic skin (Fig. 5b) was presented [100], but the output was not favorable due to the intrinsic limitation at the low piezoelectric constant of the PVDF. Consequently, poly(vinylidene fluoride trifluoroethylene) (P(VDF-TrFE)) was developed for improving the output performance of the wearable PENGs. Solution-derived P(VDF-TrFE) piezoelectric thin films on cellulose paper substrate were prepared as a flexible PENG. The proposed device was then directly attached to the back of a human hand and generated a maximum open-circuit voltage of 0.4 V at a bending frequency of 0.25 Hz [82]. However, the amount of energy harvested by the conventional flexible PENGs is still insufficient for achieving a full self-sustainability. As illustrated in Fig. 5c, Lee et al. presented a stretchable transparent PENG based on the modification of the mobility of graphene electrodes by ferroelectric P(VDF-TrFE) remnant polarization. The output performance of the stretchable PENG is up to 30 times higher than the normal PENG under an airflow at the same speed [101]. In Fig. 5d, a bio-material with piezoelectric effect, was used for developing PENG, which will be suitable for biocompatible devices [102]. Piezoelectric polymer

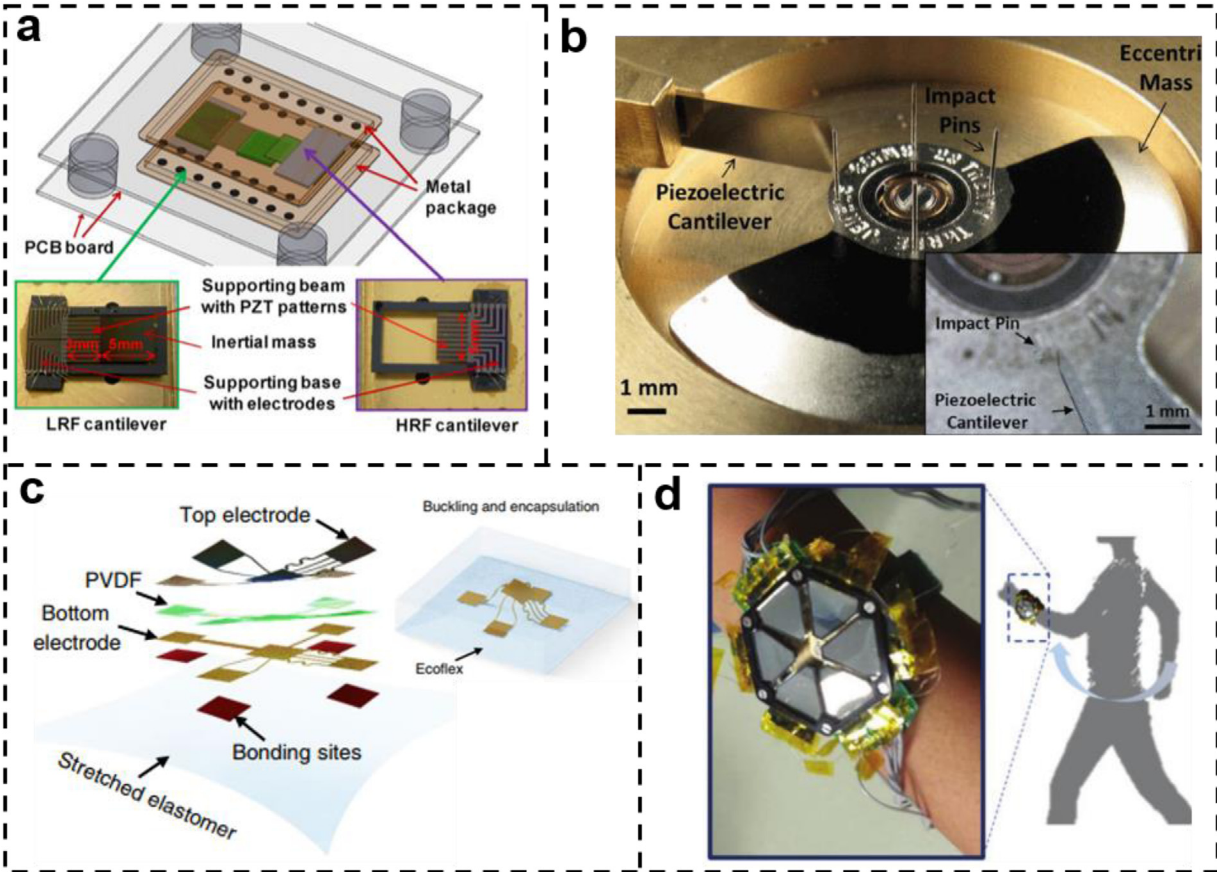

Fig. 4. Deposited piezoelectric ceramic film based wearable PENGs. (a) A piezoelectric MEMS wideband generator *via* a stopper. Printed with permission from Ref. [36]. Copyright 2012 Elsevier. (b) A micromachined wearable generator based on piezoelectric cantilevers coupled to a rotational oscillating mass. Printed with permission from Ref. [97]. Copyright 2014 IEEE. (c) Three-dimensional polymer PENG. Printed with permission from Ref. [98]. Copyright 2019 Springer Nature Limited. (d) A wrist-worn PENGs based on RF-sputtered strongly (001) oriented PZT film. Printed with permission from Ref. [99]. Copyright 2018 John Wiley & Sons.

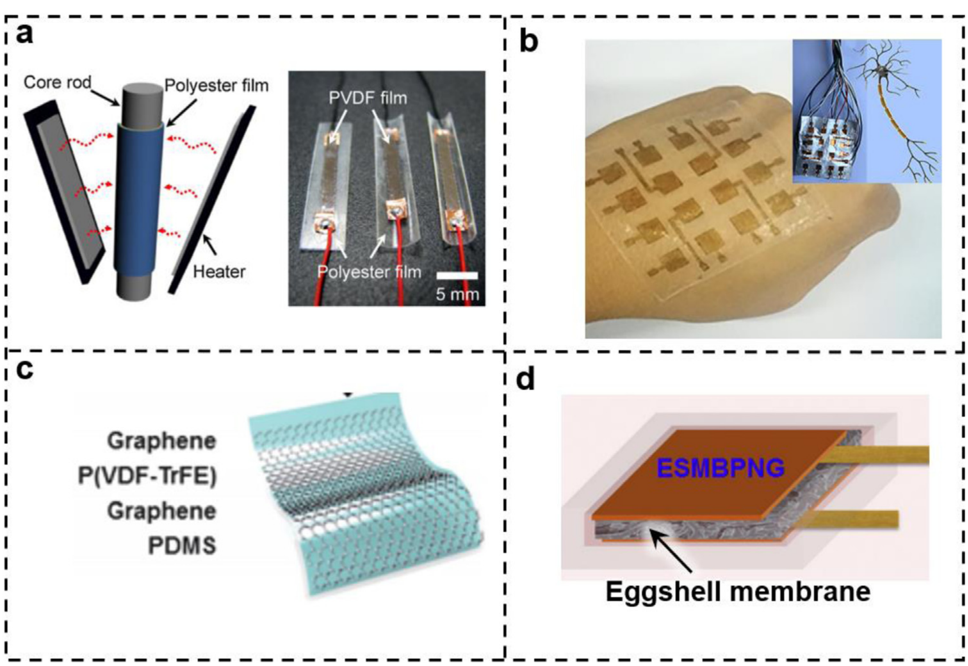

Fig. 5. Piezoelectric polymer film based wearable PENGs. (a) A shell structure PEHG for low-frequency body movement. Printed with permission from Ref. [81]. Copyright 2012 Elsevier. (b) A skin-conformal PENG. Printed with permission from Ref. [100]. Copyright 2018 American Chemical Society. (c) A stretchable transparent PENG. Printed with permission from Ref. [101]. Copyright 2013 The Royal Society of Chemistry. (d) An eggshell membrane bio-PENG. Printed with permission from Ref. [102]. Copyright 2018 Elsevier.

films possess excellent flexibility and biocompatibility, but the low piezoelectric coefficients limit the applications in wearable energy harvesting. Hence, for the current material properties, it will be more suitable for developing wearable piezoelectric sensors.

Nanowires based wearable PENGs

With the rapid development of nanotechnology, piezoelectric nanowires with electromechanical characteristics attracted more attention. Due to the flexibility and bendability, wearable PENGs based on these piezoelectric nanowires as the early applications were developed. In Fig. 6a, Zhu et al. reported the vertically aligned ZnO nanowires PENG fabricated by a scalable sweeping-printing-method could achieve an open-circuit voltage of up to 2.03 V and a peak output power density of ~11 mW/cm^3 [39]. Moreover, Lee et al. demonstrated a ZnO nanowires and a PVDF hybrid-fiber PENG [103] (Fig. 6b). However, its output performance is not ideal. To enhance the output performance, piezoelectric ceramic nanowires with a higher piezoelectric constant are used for nanowires PENG. A PZT nanowires PENG can generate 6 V output voltage and 45 nA output current [104]. However, the nanowires PENGs still face with low electrical output on the way to practical wearable applications. Moreover, it is difficult to fabricate the electrode layer for the piezoelectric nanowires film. Compositing with other materials will bring about some loss of the piezoelectric properties.

Among many wearable objects, the cloth is the preferable platform due to its available space and the abundant kinetic energy resources during the wearing. Recently, a number of works were focusing on flexible piezoelectric fibers with piezoelectric nanowires [105]. Depending on the coupled piezoelectric and semiconducting properties of ZnO, Bai et al. [106] developed a two-dimensional woven harvester as shown in Fig. 6c, which was composed of two kinds of fibers grown with ZnO nanowires crossing with each other. The generated open-circuit voltage and short-circuit current of the harvester are 3 mV and 17 pA, respectively. To improve the output performance, Zeng et al. [107] has presented an all-fiber wearable electric power harvester (Fig. 6d) based on a PVDF–$NaNbO_3$ nanofiber nonwoven fabric and an elastic conducting knitted fabric electrodes. The PENG can produce a peak open-circuit voltage of 3.4 V and a peak current of 4.4 mA in cyclic compression tests at a frequency of 1 Hz and a maximum pressure of 0.2 MPa. Given the non-uniform deformation distribution in this piezoelectric nanofiber nonwoven fabric harvester, Sone et al. [108] proposed a wearable PENG, which was composed of warp and weft threads made of yarn strings and piezoelectric film straps, respectively. Maximum power densities of 81 and 125 μWcm^{-2} can be obtained from the device using warp-thread diameters of 5 and 3 mm, respectively. To improve the flexibility of the piezoelectric fibers, a highly flexible two-ply piezoelectric yarn that consists of an electrospun PVDF–TrFE mat was developed [109]. The longitudinal tension force can be effectively converted into a transverse compression force via the plying structure. The piezoelectric yarn shows an output voltage of 0.7 V by compression in the radial direction and 0.55 V by tension in the longitudinal direction. In order to provide more energy harvesting solutions, the possibility of flexible and durable PENGs based on the simple procedure and low-cost strategies are investigated as well. Zhang et al. [110] reported a flexible hybrid piezoelectric fiber-based two-dimensional PENG as appeared in Fig. 6e. The hybrid piezoelectric fiber comprised aligned $BaTiO_3$ nanowires and PVC polymer. By attaching the fabric PENG on an elbow pad, which is bent by human arms, the device can generate 1.9 V as the output voltage and 24 nA as the output current. Additionally, a novel yarn was explored as a wearable PENG consisting of a layer of electrospun PVDF nanofibers integrated with PVDF film around a silver deposited nylon filament acting as an inner electrode [111,112]. The resultant unique yarn produced an average peak voltage of 0.52 V, peak current of 18.76 nA under a cyclic compression of 0.02 MPa at 1.85 Hz.

Wearable triboelectric nanogenerators (TENGs)

As a nanogenerator, TENGs serve as a highly customizable, flexible, and low fabrication cost power supply for wearable applications. The human body can generate a considerable amount of mechanical energy from different parts. Hence, cost-effective TENGs possess the unique advantages for applying those parts to harvest the energy efficiently [113–115]. According to the presented researches, most of those researches have used either fabric or elastomer/polymer-based materials to achieve flexibility.

Fabric-based wearable TENGs

One of the most popular research topics is to use fabric-based materials to functionalize those clothes [116]. Some commonly adopted approaches include the functional yarns with weaving or knitting techniques [117–120], and functional coating on the conventional textiles [121–124] to make the TENG integrated clothes [125–127]. A TENG made by black phosphorous (BP) with protection by hydrophobic cellulose oleoyl ester nanoparticles (HCOENPs) was developed, as shown in Fig. 7a. This fabric-based TENGs shown promising reliability under various extreme deformations and washing while still maintaining high output of ~250–880 V/cm^2. Besides, the practical wearable application also offered 60 V generated from friction with skin [128]. Subsequently, several fabrication methods of large-scale and robust textile-based TENG was illustrated [129,130]. A design of liquid- metal/polymer core/shell fibers (LCFs) was achieved by pumping liquid metal into hollow polymer fibers. For different human motions, the as-fabricated textile can generate the output voltage range from 48 V to 206 V, and a 10 μF capacitor was charged to 3 V within three minutes [131]. Using the hybrid nanogenerator concept and the specific textile fabrication process, a solar cell made of lightweight polymer fibers woven via a shuttle-flying process with fiber-based TENGs was demonstrated to make a smart fabric with hybrid power generation capabilities. Specifically, ZnO/dye and PTFE/Cu were utilized as functional materials for photovoltaic and triboelectric energy generation, respectively. Under ambient sunlight with human motion, the proposed device had a thickness of 320 μm, and can charge a 2 m F commercial capacitor up to 2 V in 1 min [132]. Moving forward, in Fig. 7b, the integration with a wearable power storage solution becomes the next approach to realize the reliable supply. For example, a supercapacitor yarn made by rGO/Ni coated polyester yarns (rGO-Ni-yarn) was introduced into the TENG cloth made by Ni and parylene coating on polyester. The robust capacitor provided a high capacitance of 72.1 m F/cm2, and the three-series yarn supercapacitor can be charged by TENG cloth to 2.1 V in 2009s [133]. Cong et al. presented a coplanar self-charging power textile featured with TENG and micro-supercapacitor (MSC) using reduced graphene oxides as active materials coated on single knitted textile (Fig. 7c). The MSC reaches a maximum areal capacitance of 50.6 m F cm^{-2} at 0.01 V s^{-1}.while the Ni electrodes maintaining good conductivity under 600 % tensile strain [134]. On the other hand, by applying the rib knitting technique, Kwak et al. proposed a fully stretchable TENG fabric with the direct available PTFE and silver fibers and the textile industry process (Fig. 7d). The as-fabricated device can generate up to 60 μW at 3.3 Hz compression [135].

Instead of textiles, the integration of supercapacitor and TENG was also reported by using 2D MXene-based solid-state micro-supercapacitors for a monolithic device in silicon rubber encapsulation, as depicted in Fig. 7e. A power density ranges from 225–755 mW/cm^3 was achieved. The triboelectric output gener-

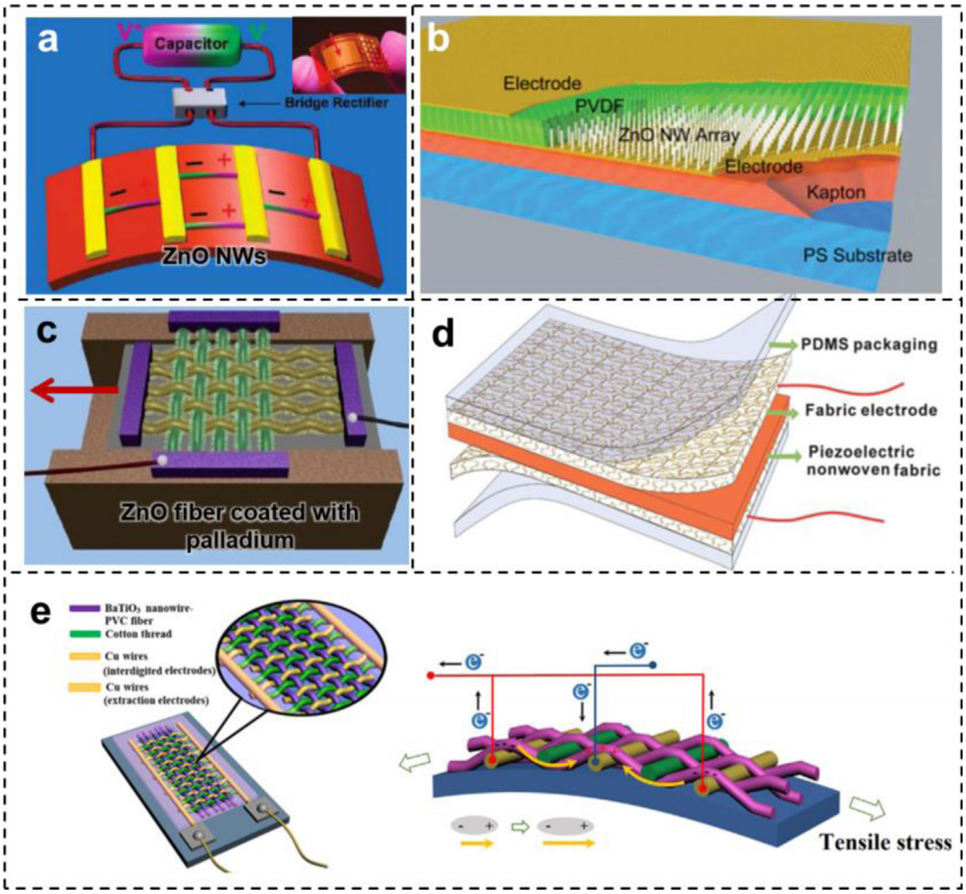

Fig. 6. Piezoelectric nanowires based wearable PENGs. (a) A flexible lateral ZnO nanowire array nanogenerator. Printed with permission from Ref. [39]. Copyright 2010 American Chemical Society. (b) A PVDF and ZnO nanowires hybrid structure nanogenerators. Printed with permission from Ref. [103]. Copyright 2012 John Wiley & Sons, (c) Two dimensional woven PENG. Printed with permission from Ref. [106]. Copyright 2013 Elsevier. (d) An all-fiber PENG. Printed with permission from Ref. [107]. Copyright 2013 The Royal Society of Chemistry, (e) A hybrid fibers based fabric PENG. Printed with permission from Ref. [110]. Copyright 2015 Elsevier.

ated from silicon and skin can charge to the capacitor to 0.11 within 200 s at 10 Hz of human motion frequency [136].

Elastomer and polymer thin-film based wearable TENGs

For wearable applications, the elastomer and polymer-based materials are also frequently adopted due to the requirements of flexibility and stretchability on the human body. As the major part of contributing the mechanical energy, footwear is drawing great attention in terms of energy harvesting [40,137]. Hence, a TENG insole with a built-in flexible stacked multi-layered triboelectric layer was fabricated. The parallel connection from the zigzag-shaped TENG units can help the open-circuit voltage add up to 220 V with a short-circuit current of 600 μA, which can successfully charge the cell phone [138]. As another design, an elastomer-based TENG insole with a stacked woven structure was developed, as illustrated in Fig. 8a, in which the carbon black and carbon nanotube mixed with elastomer were applied as a stretchable electrode. The flexibility and stretchability ensured the energy harvesting from pressing, stretching, and bending, *etc.* In general, this insole provided the maximized volume charge density of 0.055 C/m^3 under pressing motions [139].

The similar woven or wrinkled structure was also reported for harvesting the mechanical energy from the arm, due to the outstanding stretchability [140]. A transparent PDMS based TENG with PEDOT:PSS electrode was pre-stretched to create the wrinkled structure after releasing (Fig. 8b). The device showed the charging of a 22 μF capacitor to 2 V in 211 s by hand tapping [141]. Moreover, in addition to the woven structure, a fully self-healable TENG was studied by introducing the reversible dynamic imine bonds in the polymer networks of PDMS (Fig. 8c). With the buckled Ag + PEDOT electrode film, this stretchable and self-healable TENG obtained the healing efficiency of 86 % within 12 h and offered a power density of 327 mW/m^2 [142]. Meanwhile, a crumpled nanofiber membrane made by PVDF-HFP nanofiber, which had great electronegativity and high surface area, was also presented. The proposed TENG provided the instantaneous power of 0.45 mW [143]. An elastomer and hydrogel-based TENG was fabricated using PDMS encapsulated Polyacrylamide (PAAm) hydrogel with lithium chloride (LiCl) (Fig. 8d). The device possessed ultrahigh stretchability of 1160 % strain and transparency of 96.2 %. The instantaneous peak power density of 35 mW/m^2 can be obtained under 100 kPa pressure at 1.5 Hz [144].

Limited by the requirement of wearing comfortability, various strategies of boosting the output performance are investigated, especially for the in-plane displacement. For most cases, surface microstructure engineering of the triboelectric layer was applied (Fig. 8e) [145–149]. A micropillar structured PDMS film as friction layer was developed to enhance the delivery of vibration energy to TENG, as shown in Fig. 8f. As an experimental comparison, the capacitor can be charged to 0.9 V with a pillar structure during walking, which was much higher than 0.4 V for non-pillar structure [150].

By integrating TENG with other functional devices, there are diversified applications can be achieved directly. In Fig. 8g, a flexible drug delivery system powered by TENG was proposed. The power management unit can assist the steady output voltage from

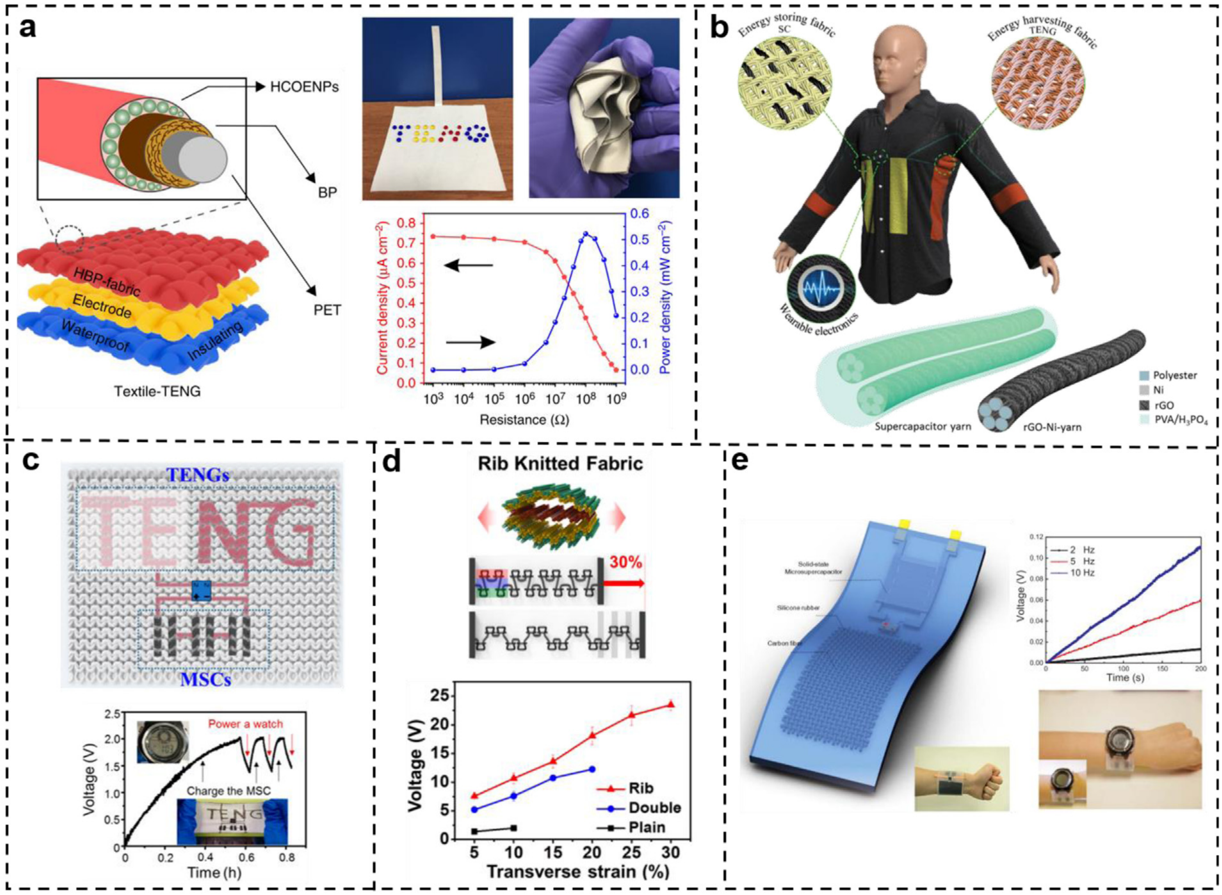

Fig. 7. Fabric based wearable TENGs for harvesting mechanical energies from body motions. (a) A textile-based TENG with black phosphorus hydrophobic coating for biomechanical energy harvesting. Printed with permission from Ref. [128]. Copyright 2018, Springer Nature. (b) A wearable self-charging textile with flexible yarn based TENG and supercapacitors. Printed with permission from Ref. [133]. Copyright 2016, John Wiley & Sons. (c) A coplanar textile with resist-dyeing TENG and micro-supercapacitors [134]. Printed with permission from Ref. [134]. Copyright 2020, American Chemical Society. (d) A textile TENG with knitted fabric structures. Printed with permission from Ref. [135]. Copyright 2017, American Chemical Society. (e) MXene based micro-supercapacitor integrated with TENG as a wearable self-charging power unit. Printed with permission from Ref. [136]. Copyright 2018, Elsevier.

TENG to supply drug release with the regulated wettability of poly(3-hexylthiophene) films in Na_2SO_4 aqueous solutions [151]. A hybridized nanogenerator with both TENG and EMG mechanisms were utilized to make a self-powered electronic watch (Fig. 8h). In this design, the magnetic ball was encapsulated by the cases with embedded coils and can generate 2.8−4 mW power under 22 Hz vibration. The underneath arch-shaped TENG made by nylon and PDMS + PVB can generate 0.1 mW power. As a result, the proposed self-powered watch can operate for 456 s after the capacitor was charged for 39 s [152]. As a complementary solution to the drawbacks of the power density of TENG, the hybridized nanogenerator plays an important role in the application with larger power consumption [113,153–155].

Implantable nanogenerators

Currently, millions of lives rely on implantable medical devices to maintain and monitor the vital signs [149]. Notably, almost all of the implantable medical devices, such as heart rate monitors, pacemakers, cardioverter-defibrillators, and neural stimulators, are still powered by energy storage components, e.g., batteries [156,157]. Thus, periodic replacement surgery is inevitable due to the limited lifetime of a battery, which greatly increases the health risks of patients with heightened morbidity and even potential mortality [158]. In order to eliminate the need for batteries, significant efforts have been made to develop PENG based self-powered medical devices. The most promising approach is to directly harvest energy from ambient mechanical motions from the body [156,158–169], such as muscle stretching, heartbeats, blood flow, gas flow due to respiration, *etc.* [170]. On the other hand, there are more candidates of triboelectric materials to assure the stretchability and the biocompatibility for implanted TENG devices. Therefore, the diversity of material selection facilitates the researches on triboelectric based healthcare applications [171–173].

Implantable PENGs

Natural mechanical motions of organs can be converted into electrical energy for powering implantable devices [156,158,161,163,164,166,174–177]. Implantable PENG technology is one of the promising approaches [178], which can provide high power density and robust stability without intrinsic limitations from others such as electromagnetic damage, surface damage from friction, or additional bias voltage [156,158,179]. The development of the implantable PENGs mainly focuses on improving the output performance and optimizing their structures to conform to the environment of internal organs [178]. *In vivo* biomechanical energy harvesting was achieved firstly via flexible PENG based on ZnO nanowires, as shown in Fig. 9a [174]. Recently, PVDF as a good flexible piezoelectric material also has been reported (Fig. 9b) [166,180,181]. However, the outputs of these devices, especially the output currents, are too low for

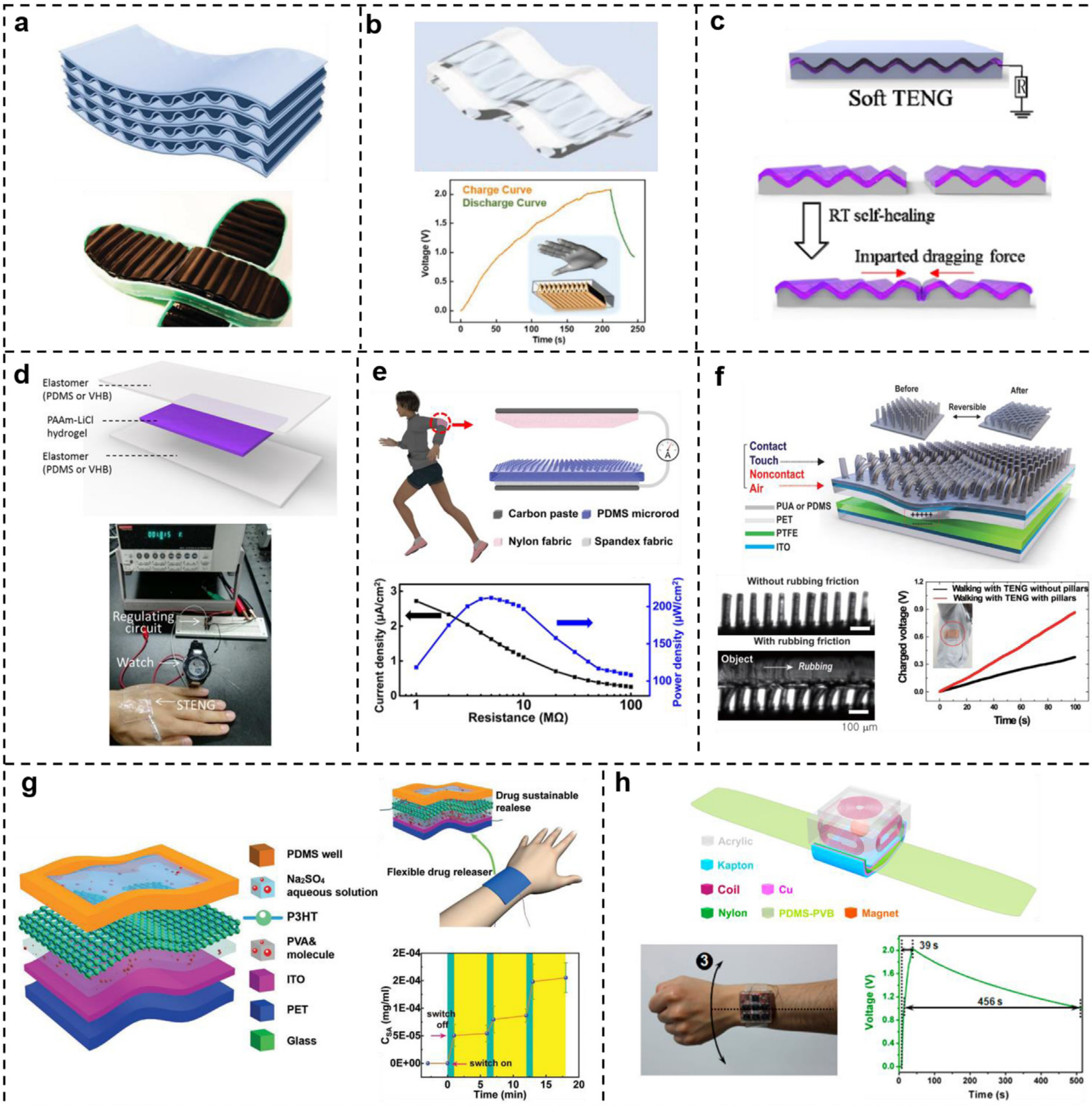

Fig. 8. Polymer and elastomer based wearable TENGs for harvesting mechanical energies from body motions. (a) A multilayer elastomeric TENG as power generating insole. Printed with permission from Ref. [139]. Copyright 2017, John Wiley & Sons. (b) Stretchable and transparent TENG with wrinkled PEDOT:PSS film. Printed with permission from Ref. [141]. Copyright 2018, John Wiley & Sons. (c) Self-healable TENG. Printed with permission from Ref. [142]. Copyright 2018, American Chemical Society. (d) Ultra-stretchable and transparent TENG as e-skin. Printed with permission from Ref. [144]. Copyright 2017, American Association for the Advancement of Science. (e) Enhancement of TENG performance with oblique microrod arrays. Printed with permission from Ref. [145]. Copyright 2019, American Chemical Society. (f) A micropillar shaped TENG for efficient harvesting of in-plane stimuli. Printed with permission from Ref. [150]. Copyright 2020, John Wiley & Sons. (g) Flexible drug release device powered by TENG. Printed with permission from Ref. [151]. Copyright 2020, John Wiley & Sons. (h) Hybridized EMG-TENG as a self-powered watch. Printed with permission from Ref. [152]. Copyright 2015, American Chemical Society.

practical applications. Therefore, high performance piezoelectric ceramic (PZT) or piezoelectric single crystal is drawing much more attention [156,158,161,182–185]. Researchers presented a flexible PZT PENG (Fig. 9c) with a maximum output current of ~0.1 μA in big animal models [156], which provided the evidence that the piezoelectric method can yield significant electrical power from motions of internal organs. In order to improve its performance, single-crystal piezoelectric material with a higher piezoelectric coefficient was used to achieve a higher output. A PMN-PT based PENG, as shown in Fig. 9d can provide sufficient electrical energy to support effective stimuli for rat heart. The *in vivo* short-circuit output current can reach 1.74 μA (Fig. 9e) [158].

Nevertheless, the energy conversion of the PENG relies on not only the advanced piezoelectric materials, but also the structural design, the implantation location, and harvesting mode [186,187]. For harvesting cardiac kinetic energy [156,158,163,164], the most reported devices are attached on the surface of the heart through suturing methods. While direct damage on the surface of the heart may cause a safety concern, and the available energy for PENGs from this approach is limited to the transverse strain. Recently, Li and Yi et al. [188] presented an integrated strategy for directly powering a full-function cardiac pacemaker using a capsular PENG as shown in Fig. 9f. The implanted PENG can generate a high output current of 15 μA over state-of-the-art performance, which demonstrated a feasible self-powered cardiac pacemaker strategy.

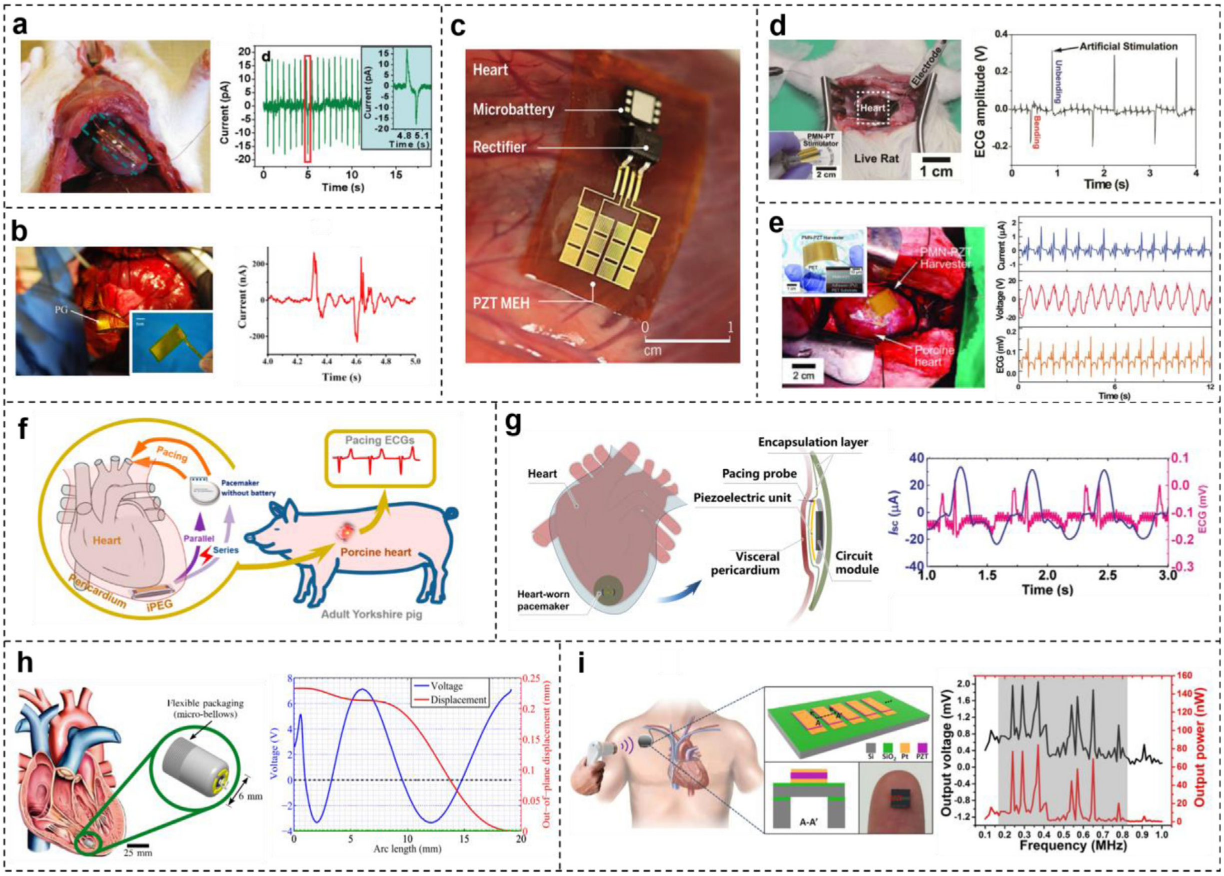

Fig. 9. Implantable PENGs as power supply. (a) ZnO based PENG attached on the mouse cardiac surface. Printed with permission from Ref. [174]. Copyright 2010 John Wiley & Sons, (b) PVDF PENG for scavenging the arterial impulse kinetic energy. Printed with permission from Ref. [180]. Copyright 2015 Elsevier, (c) Transfer printed PZT film based implantable piezoelectric cardiac kinetic energy harvester [323,156]. Printed with permission from Ref. [156]. Copyright 2014 National Academy of Sciences, (d) Single-crystal PMN-PT based implantable PENG for heart stimulator. Printed with permission from Ref. [161]. Copyright 2014 John Wiley & Sons, (e) Thinned single-crystal film based piezoelectric cardiac kinetic energy harvester. Printed with permission from Ref. [158]. Copyright 2017 John Wiley & Sons, (f) Improved cardiac kinetic energy harvester based on the piezoelectric thick film for powering commercial cardiac pacemaker. Printed with permission from Ref. [188]. Copyright 2019 American Chemical Society, (g) A battery- and leadless pacemaker strategy based on the improved single-crystal piezoelectric thick film energy harvester. Printed with permission from Ref. [189]. Copyright 2020 John Wiley & Sons. (h) A leadless cardiac pacemaker strategy based on microscale PENG. Printed with permission from Ref.[190]. Copyright 2018 IEEE. (i) Powering cardiac pacemaker by a piezoelectric ultrasonic energy harvester. Printed with permission from Ref. [191]. Copyright 2016 Springer Nature Limited.

For practical application, this PENG powered pacemaker experiences an obstacle of setting up the pacing leads. Consequently, a heart-worn pacemaker (Fig. 9g) with the batteryless powering and leadless pacing features was further explored by these researchers [189]. The batteryless feature was attained via heart-extrusion energy scavenging through a micro-machined thick film PENG, which obtained a recorded *in vivo* output current of 30 μA. The exocardial pacing method demonstrated by this batteryless pacemaker avoids a device or leads placed inside the cardiac chambers. A small volume MEMS-based PENG as shown in Fig. 9h was reported for a leadless pacemaker [190]. Acoustic energy transfer is a promising energy harvesting technology candidate for implantable biomedical devices. However, it does not show competitive strength for enabling self-powered implantable biomedical devices due to two issues: large size of bulk piezoelectric ultrasound transducers, and output power fluctuation along with the transmission distance for standing wave. Shi et al. report a MEMS based broadband ultrasonic PENG as shown in Fig. 9i to enable self-powered implantable biomedical devices [191]. At 1 cm distance, power density can be increased from 0.59 $\mu W/cm^2$ to 3.75 $\mu W/cm^2$ with an imput ultrasound intensity of 1 mW/cm^2 when frequency changes from 250 to 240 kHz.

Implantable TENGs

Similar to wearable TENG, one of the major functions of implanted TENG is to act as a power supply to various implanted medical devices [16,17,192]. Owing to the wide options of TENG materials, biocompatibility issues of implanted devices can be solved more effectively. For instance, the pacemaker is the most frequently studied devices for testing the feasibility of nanogenerator. In Fig. 10a, an implantable TENG in a living rat was reported to harvest energy from its breathing. The proposed TENG consists of Al foil and Kapton film as triboelectrification layers, which were encapsulated in PDMS. By converting the mechanical energy of breath, it provided a power density of 8.44 mW/m^2, and successfully powered a prototype pacemaker in a rat [193].

TENGs are also able to supply the power to operate the therapy and the drug delivery devices continuously [194]. Similarly, a dual arch-shaped TENG with pyramid microstructure was reported for supporting the laser cure system to improve the mouse embryonic osteoblasts' proliferation and differentiation, and shown a comparable result against the battery-powered laser cure system (Fig. 10b) [195]. Meanwhile, an in-vivo cancer therapy with a drug delivery system powered by magnet TENG was proposed, as depicted in Fig. 10c. Two magnets are used to enable the peri-

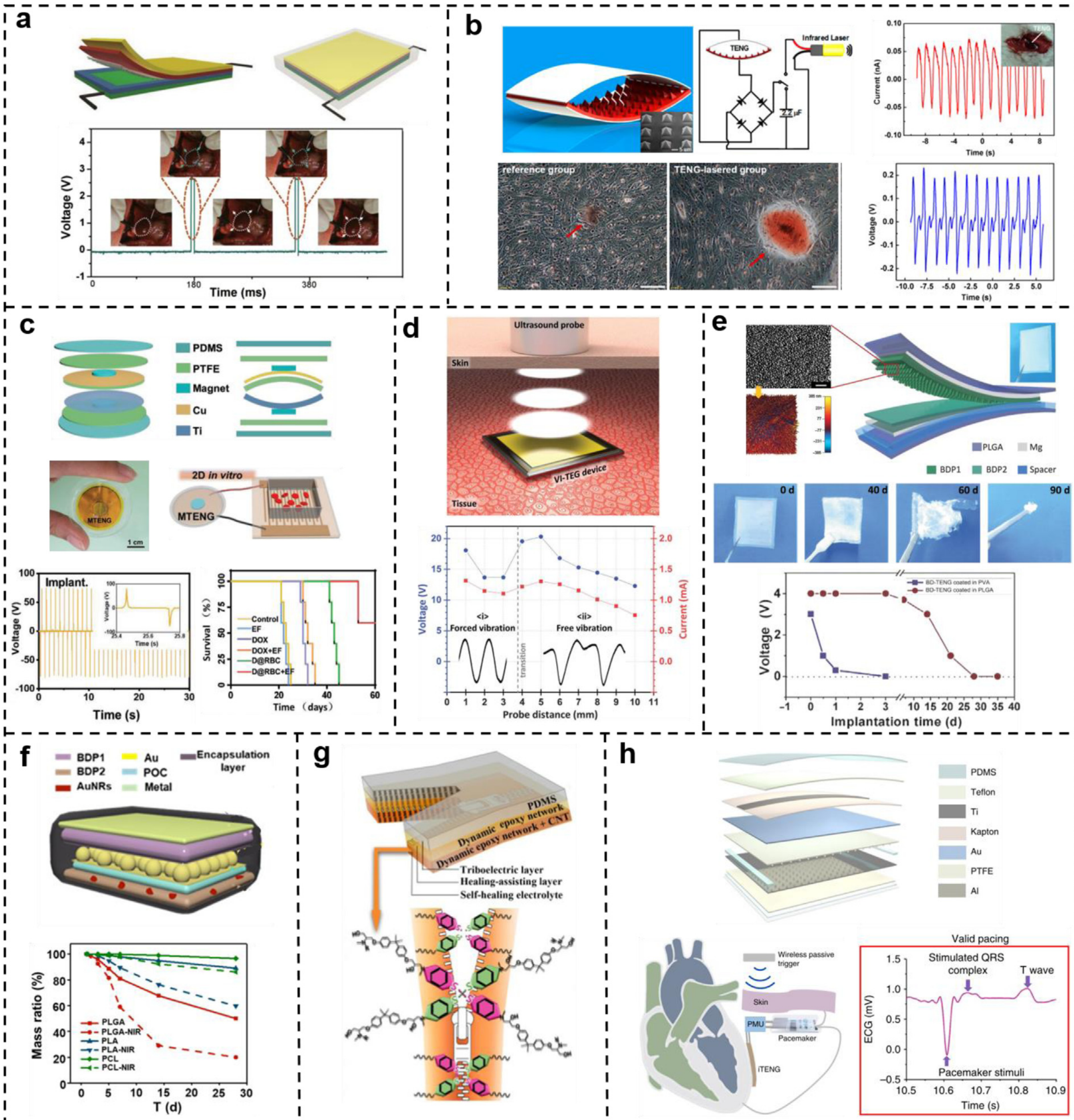

Fig. 10. Implantable TENGs for supporting the medical devices and improving the curing process. (a) *In-vivo* breathing-driven TENG for pacemaker. Printed with permission from Ref. [193]. Copyright 2014, John Wiley & Sons. (b) TENG powered laser cure system for mouse embryonic osteoblasts' proliferation and differentiation. Printed with permission from Ref. [195]. Copyright 2015, American Chemical Society. (c) Cancer therapy by an implantable magnet TENG. Printed with permission from Ref. [196]. Copyright 2019, John Wiley & Sons. (d) Ultrasound energy harvesting using capacitive TENG. Printed with permission from Ref. [200]. Copyright 2019, American Association for the Advancement of Science. (e) Biodegradable TENG with poly(L-lactide-co-glycolide) (PLGA) and poly(caprolactone) (PCL) films. Printed with permission from Ref. [203]. Copyright 2016 American Chemical Society. (f) Photothermally tunable biodegradation of implantable TENG made by Au doped PLGA. Ref. [202]. Copyright 2018 Elsevier. (g) Near-infrared irradiation induced self-healable TENGs. Printed with permission from Ref. [205]. Copyright 2018 Elsevier. (h) Implanted symbiotic pacemaker based on an implantable TENG with a shape memory alloy keel. Ref. [206]. Copyright 2019 Springer Nature Limited.

odic contacting and separation cycle for the long-term, and this structure can generate the open-circuit voltage over 70 V, and a short circuit current of 0.55 μA. The system demonstrates the powering of the delivery of doxorubicin-(DOX-) loaded red blood cells, which can greatly increase the survival rate of mice [196]. On the other hand, the rehabilitation of muscle function loss is also a major issue in healthcare, in which the main task is to restore the nervous system [17,18,197,198]. As an effective solution, the electrical stimulation of muscle plays a significant role in rehabilitation or therapy [199], however, it usually requires mA level current, which is hard to achieve by TENGs. A stacked layer TENG with flexible multi-channel intramuscular electrode design was proposed to map the motoneuron distribution and demonstrate the direct muscle stimulation of mouse. The as-fabricated device verifies the possibility for TENG to realize the self-powered muscle stimulation for restoring the motion capability of patients [19]. Recently, Hinchet et al. developed an implantable TENG for harvesting the high-frequency vibration from ultrasound to deliver the electrical power to medical systems in a long-term (Fig. 10d). The major functional part of highly integrated device consists of a thin membrane of perfluoroalkoxy (PFA) and Au/Cu electrode as triboelectrification layers. As a result, a lithium-ion battery can be charged under water at a rate of 166 μC/s by a 20-kHz ultrasound source. The in-vivo test shows the output signals of more than 2.4 V and 156 mA [200].

For other concerns of implantable device, such as biodegradation for short-term application, self-healing for long-term usage, *etc*., there are specialized functional materials which are applied to meet these requirements. Therefore, making TENGs to be the biodegradable power sources are attracting the attention in terms of materials [201,202]. For instance, a biodegradable TENG made by a biodegradable polymer and a resorbable thin Mg film electrode was proposed, as shown in Fig. 10e. The characterization of biodegradable polymer candidates shows that the combination of poly(L-lactide-co-glycolide) (PLGA) and poly(caprolactone) (PCL) can generate the largest triboelectric output. PLGA can degrade significantly within 90 days and without causing severe biocompatible issues [203]. Another attempt of using natural bioresorbable material was reported by applying silk fibroin as encapsulation, and cellulose, chitin, silk fibroin (SF), rice paper (RP), egg white (EW) as triboelectric layers. The experimental results indicate that the combination of RP and EW had the best performance in power generation, and shown a considerable degradation within 84 days. As a demonstration, the beating rates of dysfunctional cardiomyocyte clusters can be accelerated under the electrical stimulation [204]. Additionally, Li et al. has developed a biodegradable TENG with tunable degradation process via near-infrared (NIR) light (Fig. 10f), as the functional material of Au-doped PLGA film can respond to the irradiation. The proposed device can generate 2 V output in rats, and degrade within 24 days [202]. In contrast, there are researches focusing on fabricating the long-term used TENGs, since the continuous cyclic deformation may lead to permanent damage to TENGs. As an example, a near-infrared irradiation (NIR) induced remote self-healable TENG is illustrated in Fig. 10g. A disulfide bond containing vitrimer elastomer with embedded carbon nanotube (CNT) is the main functional material. The disulfide exchange reaction induced by the temperature of NIR can be further enhanced via the good NIR absorption capability of CNT, and the proposed device was able to be self-healed in a few minutes [205]. Meanwhile, the limited *in vivo* space affects the output generation of TENGs which rely on the interaction of two triboelectric layers. As depicted in Fig. 10h, Ouyang et al. proposed an implantable TENG with a shape memory alloy keel. The highly resilient titanium-based keel can effectively increase the contact area and help to increase the harvested energy up to 0.495 μJ per cycle, which is higher than the pacing threshold energy of pig [206]. The mentioned advancements of implantable TENGs are the pioneers of exploiting the potentials and feasibilities. More functional materials are deserved to be studies to further expand the *in vivo* applications.

Wearable self-powered physical sensors

Wearable PENG self-powered sensors

Piezoelectric effect has been widely developed for lots of common commercial sensors for the measurement of acceleration, acoustics, force, load, pressure, shock, strain, torque, and vibration. With the emerging of wearable electronics, there is an urgent demand for wearable sensors to obtain more information from the human body. Wearable piezoelectric physical sensing was investigated as a potential approach in healthcare monitoring [207,208], or intelligent recognition [209,210]. Recently, researches on the wearable piezoelectric physical sensors mainly focused on wearable pressure, force, strain, tension, ultrasonic sensors, and accelerometer (Table 2).

Polymer-based PENG physical sensors

Wearable piezoelectric pressure/force sensors were investigated for monitoring the motion, tactile, behavior, respiration, arterial pulse, or heart rate. PVDF as a flexible piezoelectric material was developed a film sensor with a double-sided arch structure and thin-shell structure, as shown in Fig. 11a for respiration and pulse monitoring in real-time, respectively [226]. Its flexible characteristics make the device comfortable to wear and meet the patient's daily monitoring needs. MEMS technologies and transfer printing processes are adopted for the fabrication of the epidermal PVDF sensor [227]. Given near-field electrospinning is capable of precisely deposit highly aligned micro/nanofibers, which can obtain high sensitivity. To further improve the performance, the piezoelectric ceramics or other materials were used to mix into PVDF. A piezoelectric pressure sensor based on electrospun PVDF/$BaTiO_3$ nanowire nanocomposite fibers (Fig. 11b) performs a pressure sensitivity of 0.017 kPa^{-1} in the range from 1 to 40 kPa and a response time of 290 ms [211]. Due to the good clothing-integrated characteristics of the fibers, Huang and Yang et al. fabricated flexible piezoelectric sensors (Fig. 11c) based on poly(vinylidene fluoride)/graphene composite coating on commercially available fabrics [37]. The piezoelectric sensor exhibits a sensitivity of 34 V/N and shows a low detecting threshold of 0.6 mN. In addition, a fully-printed flexible strain sensor based on P(VDF-TrFE) was developed, as shown in Fig. 11d [228], with the strain rate sensitivity about 8 V·s/m at the applying strains of 10–500 mm s^{-1}.

To enhance the effective strain in the piezoelectric layer, You et al. fabricated a 3D wave-shaped piezoelectric composite made of P(VDF-TrFE) piezoelectric film and high-elastic amorphous alloy ribbon as illustrated in Fig. 11e [229]. The wave-shaped structure produces pre-stretch in P(VDF-TrFE) film to increase the effective piezoelectric strain coefficient. An applied pressure can not only produce a compressive stress in the film, but also change the curvature and suffer stress along the length direction; therefore, it can generate a much higher voltage output. In Fig. 11f, Fuh et al. has developed wavy-substrate self-powered sensors based on near-field electrospun PVDF to monitor the foot pressure distribution [230]. For further study, Xin et al. found that the curvature of the multi-arch structure pressure sensor was one of the main factors influencing the voltage output performance of PVDF piezoelectric film [231]. The proposed sensor with a curvature of 200 m^{-1} increased the detection signal amplitude of the measurements by 141 % compared with the counterpart of the planar type. For exploiting an environmentally friendly wearable piezoelectric pressure sensor, Ghosh et al. presented a bio-inspired piezoelectric pressure sensor (~0.8 V/kPa), as appeared in Fig. 11g, from structurally stable fish gelatin nanofibers using large-area compatible electrospinning technology [218]. Flexible and stretchable electronics technologies are attracting increasing attention owing to their potential applications in personal consumed electronics, wearable human-machine interfaces (HMI), and Internet of Things [232,233]. A transparent and stretchable wearable mechanical sensor using PLA, as shown in Fig. 11h performs the sensitivity of 0.12 mV/cm^{-1} [234], with good wearability.

Ceramic based PENG physical sensors

To further improve the performance, the piezoelectric ceramics are employed for the wearable piezoelectric pressure sensor. An ultrathin flexible piezoelectric sensor based on PZT with the MEMS process for monitoring eye fatigue was fabricated [235]. Park and Joe et al. demonstrated a piezoelectric pulse sensor, as shown in Fig. 12a to obtain a sensitivity of approximately 0.018 kPa^{-1}, a response time of approximately 60 ms [212]. Then, a piezoelectric force sensor based on thinned bulk piezoelectric ceramics to monitor cutaneous activities in real-time and recognize hand gestures was proposed by Yi et al. [213,214]. The sensitivity reached

Table 2
Summary of PENG and TENG physical sensors with commonly used materials.

	Ref.	Materials	Range	Sensitivity	Response time
Piezoelectric	[211]	PVDF/$BaTiO_3$ nanowire fibers	1 to 40 kPa	0.017 kPa^{-1}	290 ms
	[37]	PVDF/GO	>0.6 mN	34 V/N	
	[212]	PZT	1 to 30 kPa	0.018 kPa^{-1}	60 ms
	[213,214]	PZT	5–500 mN	10 V/N	11 ms
	[215]	Cellular structure with PZT		0.19 V· Pa^{-1}	16 ms
	[216]	ZnO	>0.6 Pa >0.1 m/s^2 >57 dB <250 Hz	−6.8 kPa^{-1}	<5 ms
	[38]	PVDF/GO		35 nA/kPa below 2.45 kPa	
	[217]	$PbTiO_3$ nanowires/Graphene		9.4×10^{-3} kPa^{-1}	5–7 ms
	[218]	Fish gelatin nanofibers		∼0.8 V kPa^{-1}	
	[219]	$(Ba_{0.85}Ca_{0.15})(Ti_{0.90}Zr_{0.10})O_3$ (BCZT) and PDMS	5–85 kPa	0.55 V/kPa	
Triboelectric	[220]	Ag Nanowire, Silicone	<1.7 kPa	34 mV/Pa	60–90 ms
	[141]	PEDOT:PSS, PDMS and Al	2–160 kPa	0.08–0.008 kPa^{-1}	30–200 ms
	[221]	Graphene, polyethylene naphthalate (PEN), and PTFE	<100 kPa	0.04–1.63 kPa^{-1}	3 ms
	[222]	PET, ITO electrode, and PDMS	0.3–612.5 kPa	2.82 V/MPa	40 ms
	[223]	EVA, PDMS, and PET	1–80 kPa	0.06 /kPa	70 ms
	[224]	ITO, PET, Nylon, and FEP	<10 kPa	44 mV/Pa–1.1 V/Pa	–
	[144]	PAAm-LiCl hydrogel, and PDMS	1.3–70 kPa	0.013 /kPa	–
	[68]	PET, graphene, PDMS, and acrylic	1.3–101.7 kPa	0.274 V/kPa	180 ms
	[225]	Acrylic, kapton, Au, and FEP	50–110 dB	112.4 mV/dB	–

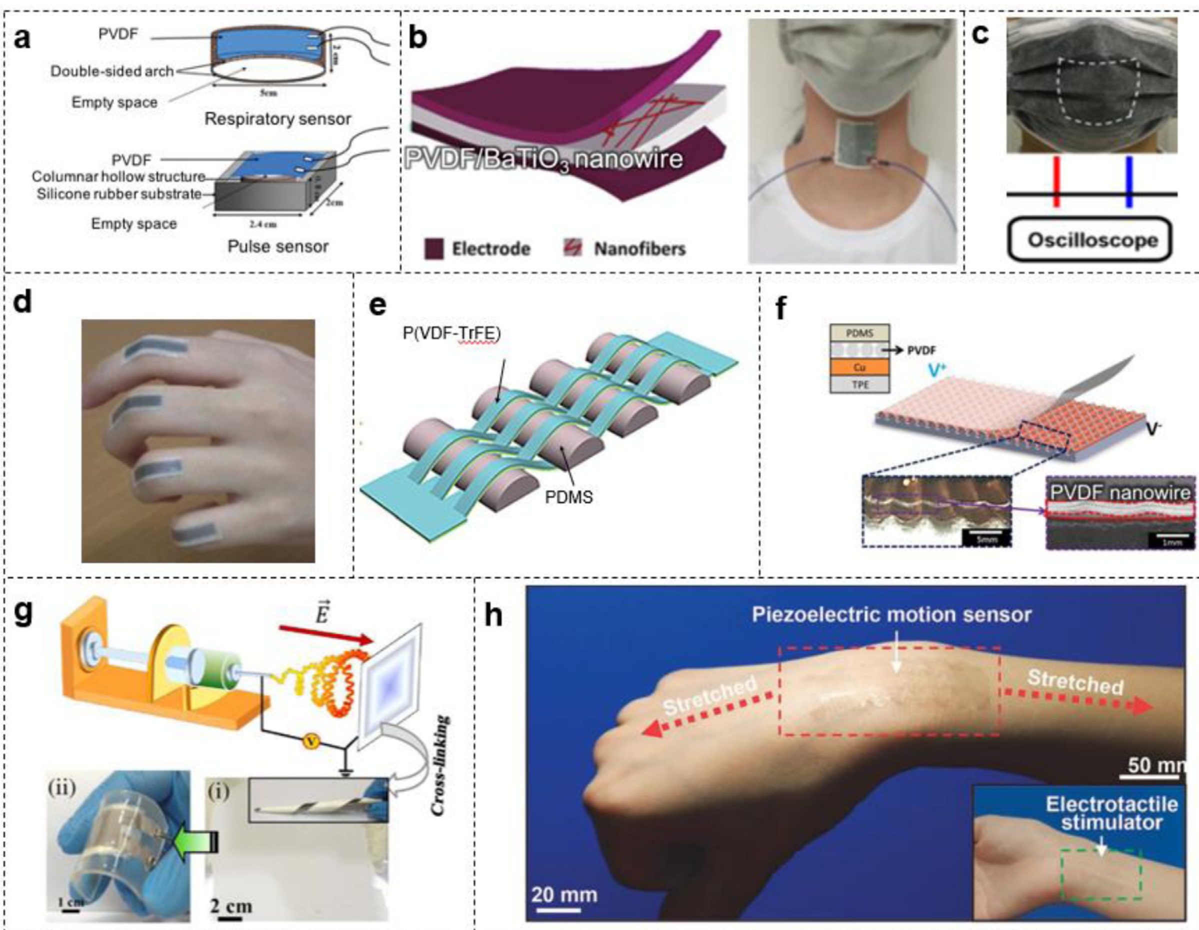

Fig. 11. Polymer-based PENG wearable physical sensors. (a) A wearable respiration and pulse monitoring system based on PVDF film. Printed with permission from Ref. [226]. Copyright 2014 Informa UK Limited. (b) Wireless piezoelectric devices based on electrospun PVDF/$BaTiO_3$ NW nanocomposite fibers. Printed with permission from Ref. [211]. Copyright 2018 the Royal Society of Chemistry. (c) PVDF/Graphene coated fabrics based flexible piezoelectric sensors. Printed with permission from Ref. [37]. Copyright 2018 American Chemical Society. (d) Ferroelectric polymer-based fully printed flexible strain rate sensors. Printed with permission from Ref. [228]. Copyright 2019 Elsevier. (e) A wave-shaped structure improved piezoelectric sensor. Printed with permission from Ref. [229]. Copyright 2016 American Institute of Physics. (f) A pressure sensor with wavy substrate and highly-aligned piezoelectric fibers array. Printed with permission from Ref. [230]. Copyright 2017 Springer Nature Limited. (g) Electrospun gelatin nanofiber sensor. Printed with permission from Ref. [218]. Copyright 2017 Elsevier. (h) A transparent and stretchable interactive human machine interface based on patterned graphene heterostructures. Printed with permission from Ref. [234]. Copyright 2015 John Wiley & Sons.

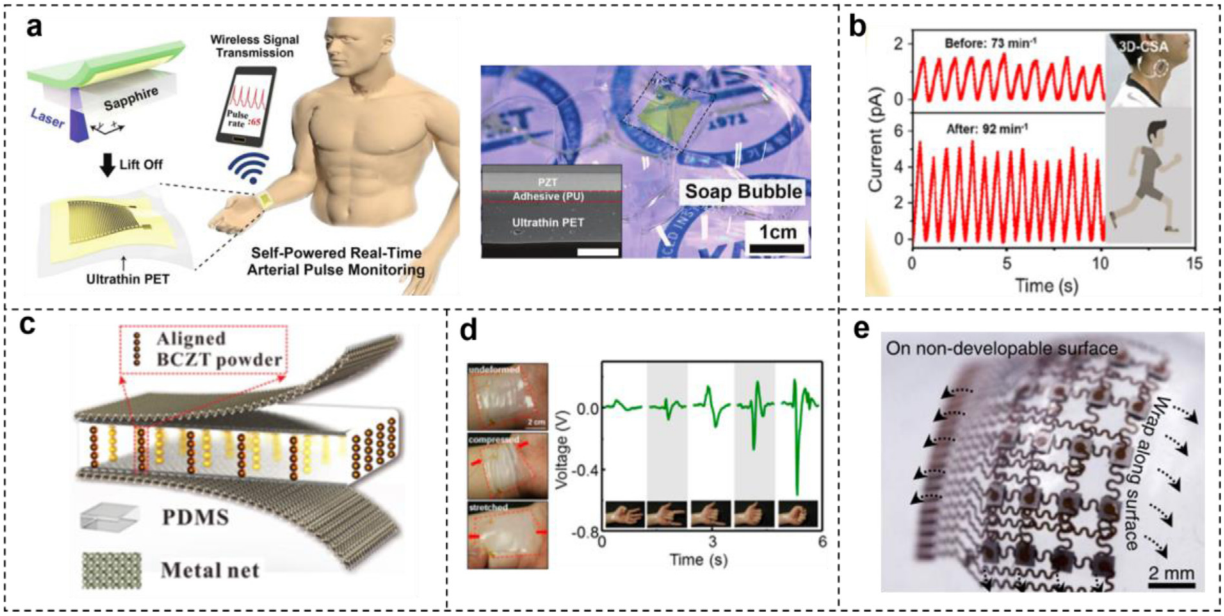

Fig. 12. Ceramic-based PENG wearable physical sensors. (a) Ultrathin epidermal piezoelectric sensors for real-time arterial pulse monitoring. Printed with permission from Ref. [212]. Copyright 2017 John Wiley & Sons. (b) Epidermis-inspired ultrathin 3D cellular sensor array for self-powered biomedical monitoring. Printed with permission from Ref. [215]. Copyright 2018 American Chemical Society. (c) A flexible piezoelectric touch sensor based on the alignment of BCZT particles in PDMS. Printed with permission from Ref. [219]. Copyright 2019 the Royal Society of Chemistry. (d) Solution-derived ZnO homojunction nanowire films sensor. Printed with permission from Ref. [236]. Copyright 2014 American Chemical Society. (e) A conformal ultrasonic sensor for monitoring of the central blood pressure waveform [244,245]. Printed with permission from Ref. [244]. Copyright 2018 American Association for the Advancement of Science.

approximately 10 V/N and the response time was 11 ms. Inspired by the configuration of the human epidermis, Yan and Deng et al. presented a flexible three-dimensional cellular sensor array based on PZT *via* a one-step thermally induced phase separation method (Fig. 12b) [215]. The sensor holds a decent pressure sensitivity of up to 0.19 V kPa^{-1} with a response time of less than 16 ms. Given the consideration of lead-free, a lead-free flexible piezoelectric sensor which was made by $(Ba_{0.85}Ca_{0.15})(Ti_{0.90}Zr_{0.10})O_3$ (BCZT) and PDMS, as depicted in Fig. 12c. A sensitivity of approximately 0.55 V/kPa and a sensing range of 5–85 kPa can be achieved [219]. To enhance wearability of the piezoelectric strain sensors, a significantly enhanced piezoelectric wearable sensor based on ultrathin ZnO p—n homojunction films was also reported (Fig. 12d) [236].

Additionally, maintaining appropriate levels of food intake and developing regularity in eating habits is crucial to weight loss and the preservation of a healthy lifestyle [237–241]. Rapid weight gain during infancy increases the risk of obesity [242]. Moreover, awareness of eating habits is an important step towards portion control and weight loss. Food-intake monitoring system based around a wearable wireless-enabled necklace attracted researchers' attention. Besides, the piezoelectric approach is explored for many kinds of sensors. Yoshida et al. developed a tension sensor with a coaxial structure using a narrow slit ribbon made of a uniaxially stretched poly(L-lactic acid) (PLLA) film for application to a wearable device [243]. The piezoelectric line has an output sensitivity per unit length of 14 pC·N^{-1} mm^{-1}. A low-profile membrane-based stretchable ultrasonic probe based on an array of thin and high-performance 1–3 piezoelectric composites was reported by Hu and Wang et al., as illustrated in Fig. 12e [244,245]. The resulting device has an electromechanical coupling coefficient of 0.60, a high signal-to-noise ratio of 20.28 dB, a wide bandwidth of 47.11 %, a negligible cross-talk level between adjacent elements of −70 dB, and a high spatial resolution of 610 mm at different depths. The "island-bridge" layout offers biaxial stretchability of more than 50 % with minimal impact on the transducer performance, which allows the device to work on nonplanar complex defects under flat, concave, and convex surfaces.

Nanowires based PENG physical sensors

Piezoelectric pressure sensor experiences the challenges in measuring static signals. A combined mechanism based on the piezoresistive and piezoelectric modes was presented for detecting both static and dynamic tactile stimuli. A sensor based on the interlocked ZnO piezoelectric nanowires as shown in Fig. 13a [216], performed a high-pressure sensitivity of −6.8 kPa^{-1} and an ultrafast response time of <5 ms in the piezoresistive mode and a high-frequency dynamic stimulus (≈250 Hz)in the piezoelectric mode. Then, the same idea to develop a fingerprint-like pattern and interlocked microstructures sensor (Fig. 13b) with a sensitivity of 35 nA/kPa below 2.45 kPa [38,246]. Additionally, a synergistic mechanism between strain-induced polarization charges in piezoelectric nanowires and the resulted change of carrier scattering in graphene was developed to resolve this problem. Chen et al. presented a pressure sensor with nanowires/graphene heterostructures based on this mechanism (Fig. 13c) [217]. This sensor performs the measurement of static pressure with a sensitivity of up to 9.4×10^{-3} kPa^{-1} and a fast response time down to 5–7 ms. The combined mechanism approach is effective in resolving the limitation of the piezoelectric sensors in static measurement. Future, the combination sensors will have great potential for wearable applications to get more tactile information.

Wearable TENG self-powered sensors

TENGs are mainly converting mechanical energy into electric energy, which offers the convenience of fabricating the self-powered physical sensors with their signals. Numbers of wearable sensors were developed to monitor the physiological signals [247,248] or capture the motions for human-machine interaction [71,114,123,137,249–253].

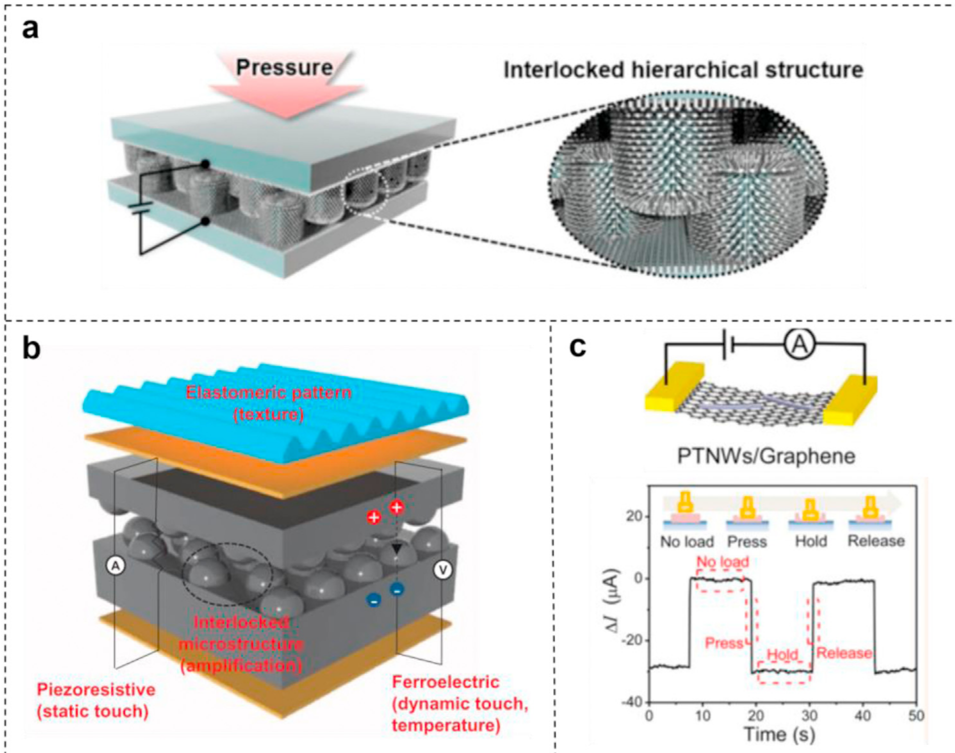

Fig. 13. Nanowires-based PENG wearable physical sensors. (a) A hybrid carbon nanomaterials functionalized strain sensor. Printed with permission from Ref. [216]. Copyright 2015 John Wiley & Sons. (b) Fingertip skin-inspired piezoelectric static/dynamic pressure and temperature stimuli [38,246]. Printed with permission from Ref. [246]. Copyright 2017 MDPI. (c) Flexible piezoelectric-induced pressure sensors for static measurements based on nanowires/graphene heterostructures. Printed with permission from Ref. [217]. Copyright 2017 American Chemical Society.

Elastomer and polymer thin-film based wearable TENG sensors

The cost-effective triboelectric materials enable the large area applications, and hence, the multi-pixel tactile sensing becomes a popular research topic in addition to pure energy harvesting. A skin-like epidermal TENG sensor for real-time motion monitoring and tactile mapping was proposed (Fig. 14a). The dots-distributed electrode pattern with the S-shaped connectors ensures the excellent stretchability and also the capability of detecting a broad range of pressure for a wide frequency range, with a thickness of 0.17 mm [254]. A transparent and stretchable TENG tactile sensor with patterned Ag-nanofiber electrodes was reported by Wang et al. (Fig. 14b), in which the electrodes were fabricated by electrospinning. The nanofiber electrodes enable a low variation of resistance of 10 % even at 100 % strain. With a cross-bar type electrode for the sensing array, the as-fabricated TENG tactile sensor can trace the writing trajectory as a wearable touchpad [255].

So far, most of these sensor arrays are using multiple electrodes to read out the signals from a specific touchpoint, which eventually increases the difficulty of signal processing. To address this issue, in Fig. 14c, a facile designed elastomer-based TENG touchpad was proposed. A 5 $\times$ 5 matrix is separated by the grid patterns, and two pairs of counter electrodes are embedded at four edges of the matrix. As each touch induced triboelectric output can have the different readout from different electrodes according to the corresponding distance from the touch point, each pair of electrodes can then identify the position via voltage ratio for either X or Y axis [256]. Moreover, by applying thin graphene, PTFE, and PDMS as the electrode, substrate, and triboelectric layer, respectively, an ultrathin (18 μm) auxetic mesh-structured stretchable TENG was fabricated as e-skin electronics with a 8 $\times$ 8 array (Fig. 14d) [68]. In addition, with the specially designed electrode patterns, the realization of multi-functional manipulation becomes possible by using fewer or even a single electrode. For example, a bio-inspired spider net-shaped coding interface using a single electrode was developed. All of the eight sectors have the electrodes with different design parameters, such as wide, separation distance, amount, and sequence *etc.*, since the triboelectric output peaks, amplitude, intervals can be tuned by those factors. Hence, by further processing those pulse waveforms into square waveform, the control command can be identified as the finger sliding across the corresponding sector (Fig. 14e) [47,48,257].

A smart insole made by a convex TENG on top of an elastic air chamber was proposed as a real-time multifunctional gait monitor, in which the TENG sensor consisted of rubber and copper layers (Fig. 17a). The device can identify various gait patterns, such as jump, step, run, and walk, *etc.* [258]. A similar structure was also utilized for sensing the mechanical micromotion of the skin around the corners of the eyes to develop the trigger on ordinary glasses (Fig. 15b). The eye blink motion can generate the output signal of 750 mV, which enabled hands-free inputs or control of appliances via programming of signals for the disabled persons [259]. Further optimization can realize the sensing of the acoustic signal as well, to create the electronic hearing platform [260,261]. A triboelectric cochlea (TEC) device for an intelligent auditory system was presented, it consists of a fluorinated ethylene propylene (FEP) with hole channels, a spacer, and a kapton membrane. The acoustic wave-induced membrane vibration causes the electric signal output. By tuning the inner boundary architecture, the device achieves the tunable frequency response for accurate acoustic sensing performance, which show great potential in medical hearing aids, home security, and self-powered auditory system *etc.* [225]. There are also various wrist bands and leg bands presented for monitoring human motion and recognizing the identities [262]. A simple designed TENG band consists of a rubber tube filled with physiological saline was demonstrated to monitor muscle contraction and expansion during walking as shown in Fig. 15c, due to the

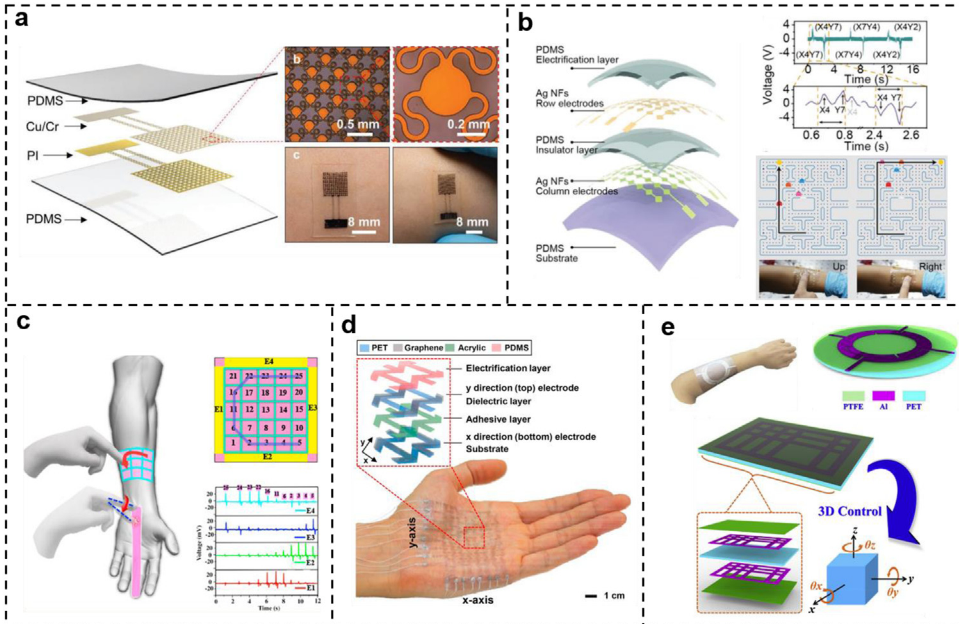

Fig. 14. Elastomer and polymer based wearable TENG sensors as multi-pixel touch pad for human machine interactions. (a) A skin-integrated stretchable TENG for tactile sensing. Printed with permission from Ref. [254]. Copyright 2020, John Wiley & Sons. (b) A transparent TENG tactile sensor array with metallized nanofibers. Printed with permission from Ref. [255]. Copyright 2018, John Wiley & Sons. (c) Elastomeric flexible patch as 3d motion control interface. Printed with permission from Ref. [256]. Copyright 2018, American Chemical Society. (d) Graphene-based touch sensor. Printed with permission from Ref. [68]. Copyright 2019, Elsevier. (e) Single-electrode-output control interface using grid electrode. Printed with permission from Ref. [257]. Copyright 2019, Elsevier. Ring patterned electrodes for a flexible wearable control interface. Printed with permission from Ref. [48]. Copyright 2019, Elsevier.

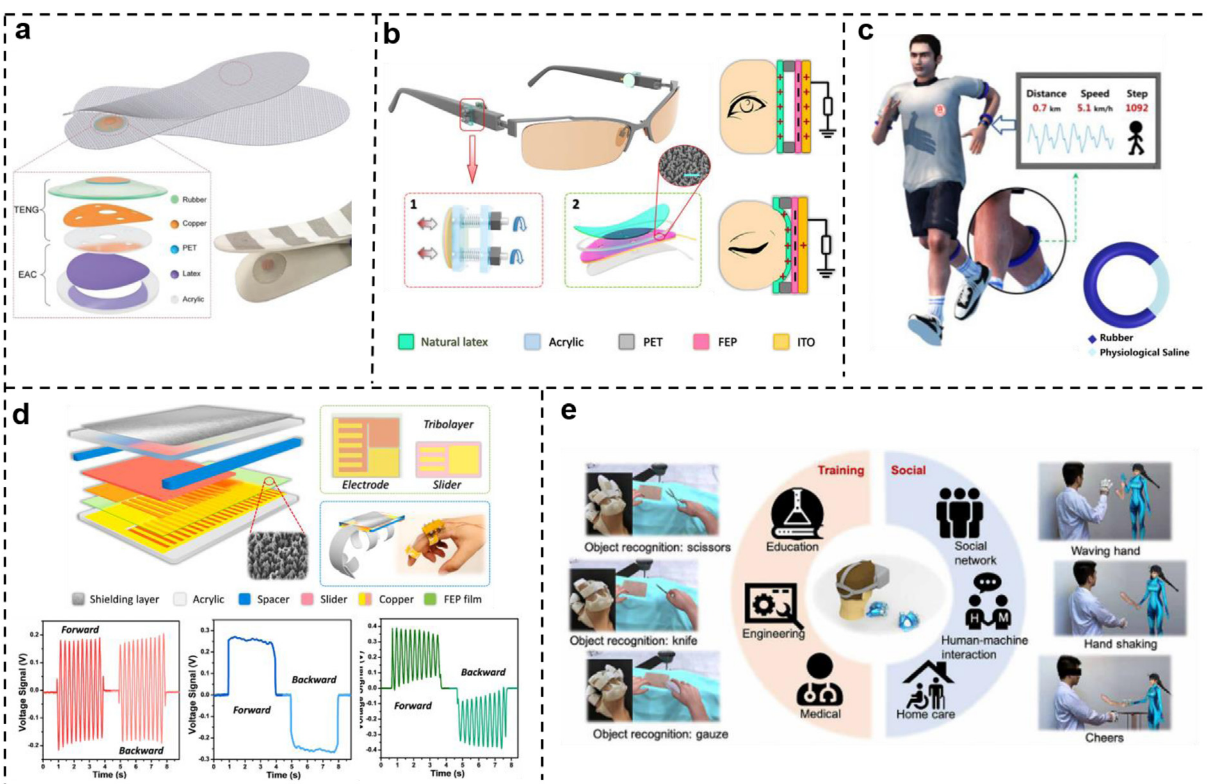

Fig. 15. Elastomer and polymer based wearable TENG sensors for the multi-dimensional detection of human motions. (a) TENG insole for multifunctional gait monitoring. Printed with permission from Ref. [258]. Copyright 2018, John Wiley & Sons. (b) Eye motion triggered mechnosensational communication system. Printed with permission from Ref. [259]. Copyright 2017, American Association for the Advancement of Science. (c) Gait pattern recognition by a TENG band. Printed with permission from Ref. [263]. Copyright 2019, Elsevier. (d) Quantization of rotation sensing and gesture control of a robot joint. Printed with permission from Ref. [266]. Copyright 2018, Elsevier. (e) Glove-based control interface with TENG sensor and PENG stimulator using machine learning technique. Printed with permission from Ref. [267]. Copyright 2020, American Association for the Advancement of Science.

triboelectrification between skin and rubber layer. Various signals from corresponding human activities can be monitored for healthcare and recognition, such as walking, breathing, swallowing, and arm curling, *etc.* [263].

Besides, owing to the sliding mode of TENG, the strain sensors are feasible of using this mechanism with lower cost and simpler design. A stretchable TENG strain sensor was reported with a piece of stretchable rubber and Al film. The outward stretched rubber can lead to contact area variation against Al film and caused the triboelectric output. Hence, the strain information can be determined based on the output amplitudes, which are applied for human motion monitoring [264]. Additionally, to quantify the stretching length of the strain sensor, the strain gauges for static and dynamic measurements were developed. There are sensors consisted of stretchable parts with protrusions and flexible parts with the grated electrodes. As a result, the grating structure can generate the sequential output peaks as the strip is stretched and slided across it. Hence, the strain due to bending or elongation can be digitalized [265]. Furthermore, a bi-directional bending sensor was proposed by adding the extra blocks next to the grated electrodes. The unique design induces the coupled signals with the features from both the grating structure and the block structure, which represent the motion distance and the direction, respectively (Fig. 15d) [266].

Recently, various sensory gloves are reported to accomplish the tasks of capturing the dexterous motions of hand. Some of them are also introduced together with AI techniques to exploit the advanced functions without the upgrade of devices. In Fig. 15e, Zhu et al. proposed a smart glove equipped with TENG based finger bending sensor and palm sliding sensor, which were made by silicone, and the PZT chips as haptic feedback stimulators [267]. Except for the standard usages of detecting finger motions and interaction with objects, the implementation of a machine learning algorithm also allows the basic object recognition capability with high accuracy, which brings more convenience to HMI for the virtual world.

Fabric based wearable TENG sensors

As mentioned in the energy harvesting TENG part, the wearable TENG based sensors can also be fabricated with functional textiles. As shown in Fig. 16a, a single thread based TENG was fabricated using silicone coated stainless steel, which performed the various abilities, such as gesture sensing, human-interactive interfaces, and human physiological signal monitoring [268]. A wearable fabric TENG touchpad made by commercialized Ni-coated fabrics attached to a cotton substrate was reported. To form a crossline array, seven columns and rows of electrodes are designed as depicted in Fig. 16b, and each long string-shaped column or row of electrodes had seven η-shaped unit cells. Each pixel is then formed by the cross-point of a row and a column. With a PTFE stylus written on the touchpad, the traces can be recorded from the sliding induced triboelectric output for the application of human-machine interaction [269]. In addition, a TENG textile made by conductive textile with silicone coating and nitrile was reported by He et al., as shown in Fig. 16c. By applying a high-voltage diode and a textile-based switch, the proposed device not only can provide enough electrical energy, but also can be utilized as a wearable communication board for healthcare [59].

Similar to the pure wearable TENGs, there is also an important research direction for utilizing the industrial fabrication technique of textile to develop the fabric based TENG sensors. A 3D double faced interlock fabric TENG was reported designed as TENG sensors for monitoring the bending degree and pressure, as shown in Fig. 16d. With a double needle bed flat knitting technology, the cotton yarn and the composite yarn can be knitted to optimize the triboelectric output [270]. Meanwhile, in Fig. 16e, Ma et al. presented a continuous and scalable manufacture process to produce a single-electrode TENG yarn featured with the helical core–shell fiber. This ultralight (0.33 mg/cm) TENG can be easily integrated in a glove, or be knitted into a smart textile for making a tactile sensor array [271].

Additionally, for relieving the influence of humidity from sweat, a pure textile-based glove (Fig. 16f) with an arched strip sensor was also developed by Wen et al. [272]. A superhydrophobic material using thermoplastic elastomer mixed with carbon nanotubes is selected as triboelectric material. This proposed glove with superhydrophobic materials shows a much faster signal recovery speed after sweating. This approach offers a promising and comfortable solution for machine learning enhanced HMI. Furthermore, there are emerging research direction regarding the integration of nanophononics to improve the sensing performance of TENG sensors [273]. The TENG sensory glove can perform the stable force sensing by integrating AlN Mach–Zehnder interferometer (MZI) modulator, which also enables the high speed data transmission [274].

Implantable self-powered physical sensors

Instead of powering the implantable electronics, the particular requirements of *in vivo* devices, such as size and long-term usage, also shows the necessity of developing the standalone self-powered sensors. The direct vital signs monitoring with PENG and TENG will significantly reduce the system complexity and the potential health risks.

Implantable PENG self-powered sensors

Owing to the good output performance, the direct measurement of vital signs *via* the piezoelectric output were presented recently [275]. As illustrated in Fig. 17 a, Han et al. proposed a three-dimensional (3D) piezoelectric microsystem by using a nonlinear buckling process to convert the two-dimensional (2D) pattern [98]. The as-fabricated device can act as a multi-directional sensor for *in-vivo* applications, such as the detection of muscle behavior during movement, with ultralow-stiffness. In Fig. 17b, Dagdeviren et al. presented a conformal piezoelectric sensor for monitoring the soft tissue viscoelasticity in the near-surface regions of the epidermis [177]. The sensor composes of stretchable networks sensors made by nanoribbons of PZT. It can help to examine microscale disorders related to mechanical property changes over time for clinic application. In addition, with the aid of various coating of enzymes, the piezoelectric sensor also can respond to the chemical variation of body fluids. Zhang et al. reported a self-powered glucometer for in-vivo real-time monitoring, as illustrated in Fig. 17c. The fabricated ZnO nanowire arrays is coated by glucose oxidase (GOx), and the coupling effect between enzymic reaction and the piezo-screening effect leads to the variation of piezoelectric output under applied force when the device is immersed in the solution of different glucose concentrations [276].

Implantable TENG self-powered sensors

The available biocompatible and flexible materials also bring the feasibility of fabricating the self-powered implantable TENG sensors through the improvements of sensitivity and output power. As shown in Fig. 18b, an arch-shaped TENG made by PTFE film is demonstrated to power the wireless transmission coil by charging the capacitor in PMU, and the power density of 107 mW/m^2 can be achieved. In the meantime, the output signals with the heartbeats waveforms can then be sent out for monitoring [163]. Furthermore, the microstructure design of triboelectric layer can enhance the sensitivity, as well as the power generation capability. Hence, an

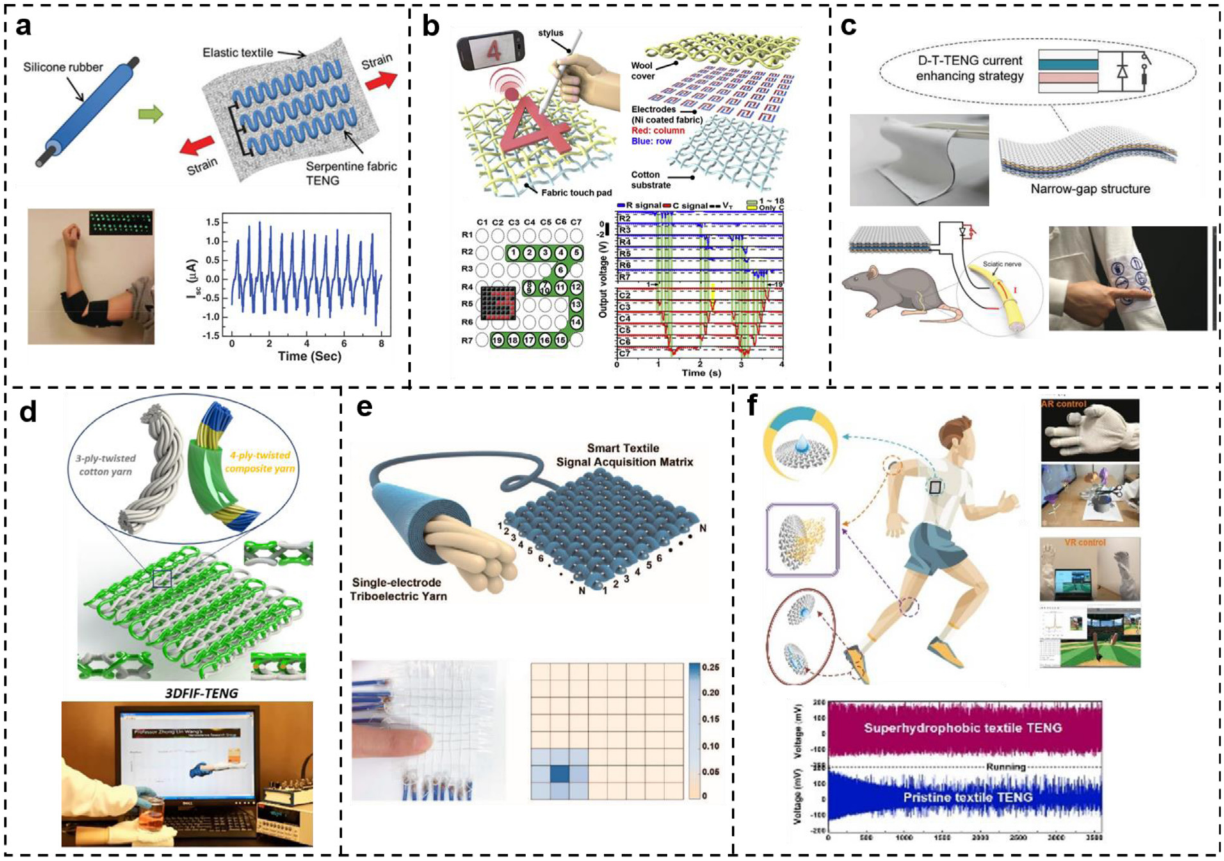

Fig. 16. Fabric based wearable TENG sensors for the multi-dimensional detection of human motions. (a) Single-thread-based TENGs for human-interactive and biomedical sensing. Printed with permission from Ref. [268]. Copyright 2017, John Wiley & Sons. (b) Wearable touchpad composed of all commercial fabrics with crossline array. Printed with permission from Ref. [269]. Copyright 2019, Elsevier. (c) Textile based TENG for healthcare applications [59]. Printed with permission from Ref. [59]. Copyright 2019, John Wiley & Sons. (d) TENG sensors with 3D double-faced interlock fabric. Ref. [270]. Copyright 2020, Elsevier. (e) A single-electrode triboelectric yarn sensor array with helical core–shell fiber. Ref. [271]. Copyright 2020, American Chemical Society. (f) A conductive superhydrophobic triboelectric textile made by thermoplastic elastomer and carbon nanotube for gesture recognition. Printed with permission from Ref. [272]. Copyright 2020, John Wiley & Sons.

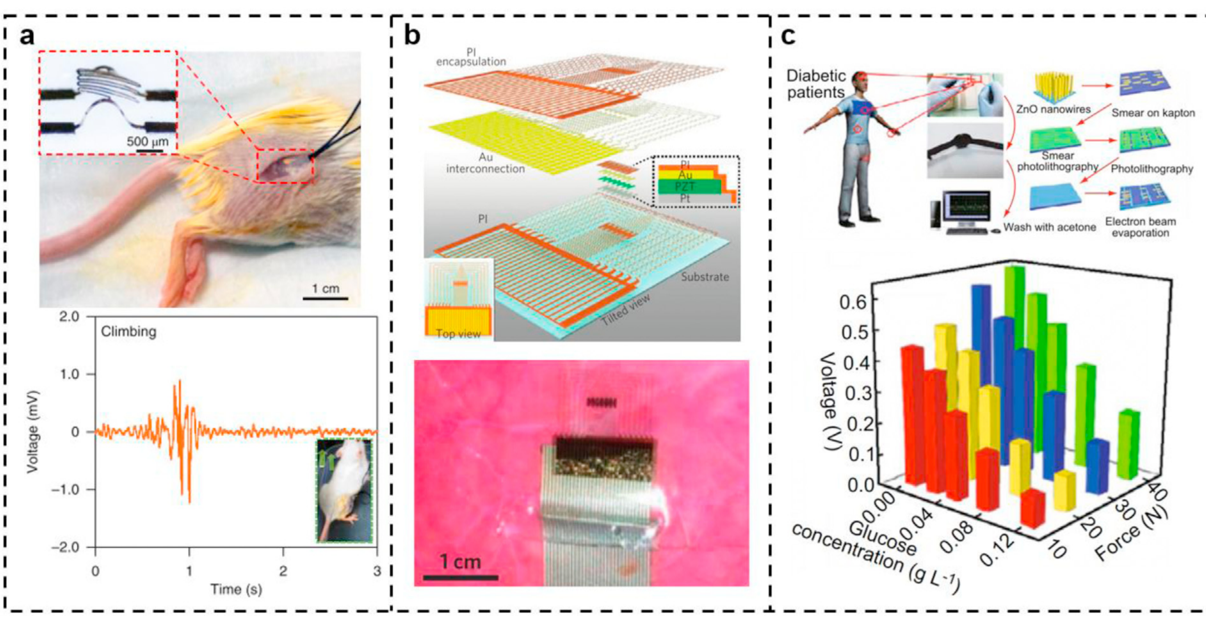

Fig. 17. Implantable PENG based self-powered sensors. (a) Three-dimensional polymer microsystems for biomedical implants. Printed with permission from Ref. [98]. Copyright 2019 Springer Nature Limited. (b) Conformal piezoelectric systems for obtaining soft tissue biomechanics information. Printed with permission from Ref. [177]. Copyright 2015 Springer Nature Limited. (c) A self-powered implantable skin-like glucometer for real-time monitoring blood glucose level *in vivo*. Printed with permission from Ref. [276]. Copyright 2018 Nano-Micro Letters.

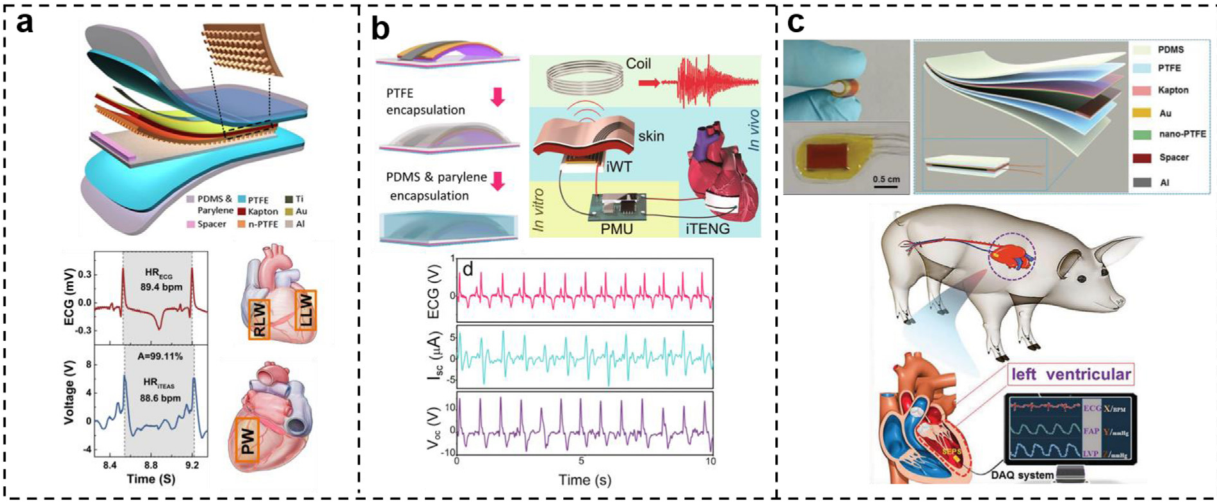

Fig. 18. Implantable TENG based self-powered sensors. (a) *In-vivo* TENG powered wireless cardiac monitoring. Printed with permission from Ref. [163]. Copyright 2016, American Chemical Society. (b) TENG active sensor for real-time biomedical monitoring. Printed with permission from Ref. [164]. Copyright 2016, American Chemical Society. (c) TENG based endocardial pressure sensor for real-time monitoring with ultrasensitivity. Ref. [277]. Copyright 2019, John Wiley & Sons.

implantable TENG active sensor was developed for accurate, continuous, and real-time monitoring of multiple physiological and pathological signals. By attaching on the pericardium, the patterned structure can detect small changes of motions of circumferential organs with an open-circuit voltage of ~10 V (Fig. 18b) [164]. Liu et al. has reported a TENG-based endocardial pressure sensor for real-time monitoring, as illustrated in Fig. 18c. The proposed TENG sensor can convert the mechanical movements of blood flow of the heart chambers into the electrical output. The surface of PTFE film was treated by inductively coupled plasma to create nano-structure for enhancing the sensitivity up to 1.195 mV/mmHg. Hence, the signals of electrocardiography and femoral arterial pressure are able to be obtained by attaching the device on the left ventricle and the left atrium [277].

Emerging research directions of IoT sensory system

As a prospect for the system with the PENG and TENG based nanogenerators and sensors, the next generation of sensory system will shed the light to the sustainable IoT networks. By considering the individual features of these two mechanisms, the different research concentrations are recognized according to the current achievements.

Wireless sensor network with PENG

Wireless healthcare monitoring with PENG

With the rapid emerging of novel wearable electronics piezoelectric wearable devices were widely investigated as a body sensor network for healthcare monitoring or motion recognition due to its low power consumption. Fig. 19a shows a wearable heart rate monitoring system by sensing in-ear pressure with a piezoelectric sensor. The system utilizes radio frequency on the 2.4 GHz band for wireless transmission [278]. An ultra-low power consumption can maintain their normal operations. As depicted in Fig. 19b, Shin et al. demonstrated a highly sensitive, wearable, and wireless pressure sensor based on the ZnO-nanoneedle/PVDF hybrid film. Due to the high permittivity, low polarization response time, and outstanding durability of the ZnO-nanoneedle, the hybrid film performed the lowest detectable pressure of 4 Pa [279]. The arterial pressure signals were transmitted to a smart phone by using a Bluetooth transmitter. Furthermore, the reduced graphene oxide (rGO) electrode-based Bluetooth antenna is used to attain a high peak gain of 2.70 dBi, which offers a promising tool for wireless pressure monitoring in critical healthcare. Meier et al. provided an energy-harvesting, shoe-mounted system for medical sensing using piezoelectric transducers for generating power (Fig. 19c) [280]. The sensing electronics are completely powered by the harvested energy from walking or running, generating 10–20 μJ of energy per step that is then consumed by capturing and storing the force sensor data. Park et al. developed a self-powered piezoelectric pulse sensor for in vivo measurement of radial/carotid pulse signals in near-surface arteries (Fig. 19d) [212]. The sensor performed a sensitivity of 0.018 kPa^{-1} and a response time of 60 ms. Wireless transmission of the arterial pressure signals to a smartphone by using a Bluetooth transmitter demonstrated the possibility of a self-powered and real-time pulse monitoring system. Yi et al. proposed a wireless piezoelectric pulse sensor based on near field communication technology (Fig. 19e) [214], which greatly decreased the volume and enhanced its wearability.

Wireless human–machine interface with PENG

Wireless HMIs are frequently adopted in our daily life for our convenience. In Fig. 20a, a wireless data glove with pneumatic actuator and flexible PVDF based piezoelectric sensor was proposed by Song et al. By analyzing the relationship between the bending induced piezoelectric output and the bending angle. The proposed glove can offer a solution for the virtual hand manipulation via the data glove [281]. Cha et al. reported a human–machine interface glove using flexible PVDF sensors, which were used to detect changes in the angles of the finger joints [233]. Data transmission module was attached on the wrist for portable wearing. The digitalized outputs of the analog–digital converter was transferred to the computer with the virtual reality program through RS-232 serial communication with a baud rate of 115200 bps. The virtual hand can be controlled well by this interface glove. Similar research was reported by Volkingburg et al., as shown in Fig. 20 [232]. They fabricated a wearable gesture-based controller by using the PVDF sensors. The controller can repeatedly and accurately discern, in real time, between right- and left-hand gestures. The Bluetooth transmitter was used for its wireless communication. In human-machine interface, it is difficult to get a static recognition by the piezoelectric sensors due to its poor static sensing. Therefore, the high precise operations usually require the joint work with other sensors, such as piezoresistive sensors. Development of human–machine interface with PENG mainly focus on the sim-

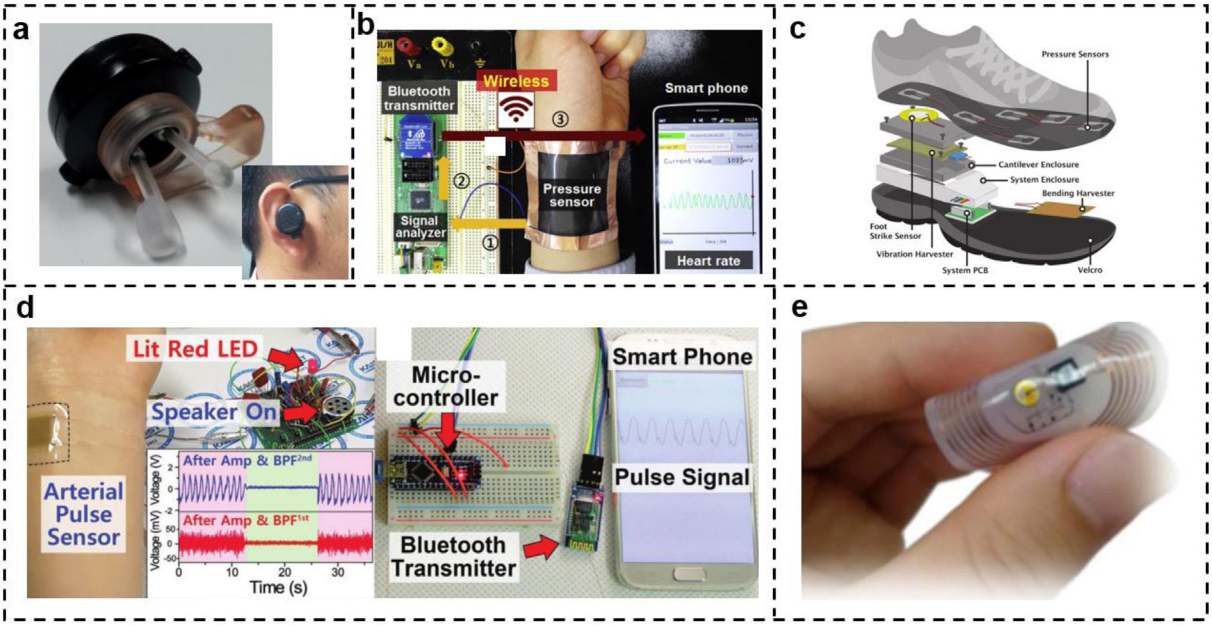

Fig. 19. Wearable PENG sensors based wireless devices for healthcare monitoring. (a) Wearable sensing of in-ear pressure for heart rate monitoring. Printed with permission from Ref. [278]. Copyright 2015 MDPI. (b) Highly sensitive, wearable and wireless pressure sensing for heart rate monitoring. Printed with permission from Ref. [279]. Copyright 2016 Elsevier. (c) A piezoelectric energy-harvesting shoe system for podiatric sensing. Printed with permission from Ref. [280]. Copyright 2014 IEEE. (d) Self-powered real-time arterial pulse monitoring. Printed with permission from Ref. [212]. Copyright 2017 John Wiley & Sons. (e) A portable, wireless wearable piezoelectric arterial pulse monitoring system based on near-field communication approach. Printed with permission from Ref. [214]. Copyright 2020 IEEE.

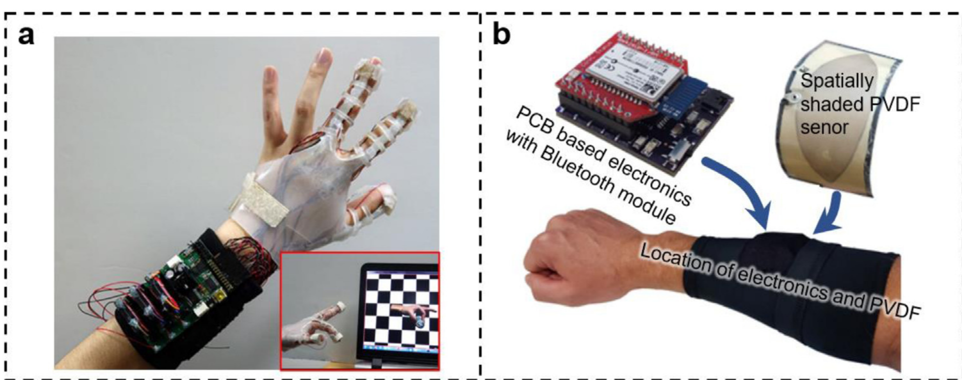

Fig. 20. Wearable PENG sensors based wireless devices for human-computer interface. (a) A data glove with pneumatic actuator and piezoelectric sensor for VR control. Printed with permission from Ref. [281]. Copyright 2019, Springer Nature. (b) A wearable controller for gesture-recognition. Printed with permission from Ref. [232]. Copyright 2017, IEEE.

ple judgement of the beginning and end over the whole operation process.

Wireless behavior recognition with PENG

Maintaining appropriate levels of food intake and developing regularity in eating habits is crucial to weight loss and the preservation of a healthy lifestyle [239,240]. Fig. 21a introduces a food-intake monitoring system based around a wearable wireless-enabled necklace with a Bluetooth transmitter. Motions in the throat were captured and transmitted to a mobile application for processing and user guidance. Additionally, rapid weight gain during infancy increases the risk of obesity. Fig. 21b shows piezoelectric jaw motion sensor and a video camera for examining infant sucking count during meals [237]. Signals were transmitted *via* Bluetooth wireless connection in real time. To get higher precision, Farooq et al. trained two separate linear support vector machine classifiers for food intake and activity detection, which resulted in a weighted average of precision and recall of 99.85 % (Fig. 21c) [242]. The Bluetooth module is used for its wireless data transmission. Unlike the previous state-of-the-art piezoelectric sensor based system that employs spectrogram features, Hussain et al. tried to fully exploit time-domain based signals for optimal features (Fig. 21d) [241]. They demonstrate that the chewing sequence carried important information for food classification. The system yields an accuracy of 89.2 % for food intake detection and 80.3 % for food classification over 17 food categories. The hardware system is interfaced with the smartphone application through Bluetooth. Besides, patient adherence is critical to the successful treatment of many diseases, as well as the effective assessment of treatment effectiveness for research purposes. A two-step system was proposed for detecting when a pill bottle was opened using commercial wireless smart-bottle technologies with Bluetooth transmission and when a pill was consumed using a custom-designed wireless smart necklace with RF communication using a piezoelectric sensor (Fig. 21e) [240]. These two mechanisms with the mobile application can passively monitor adherence and inform caregivers of patient status. Kim and Lee presented a flexible wireless electronic skin sensor system

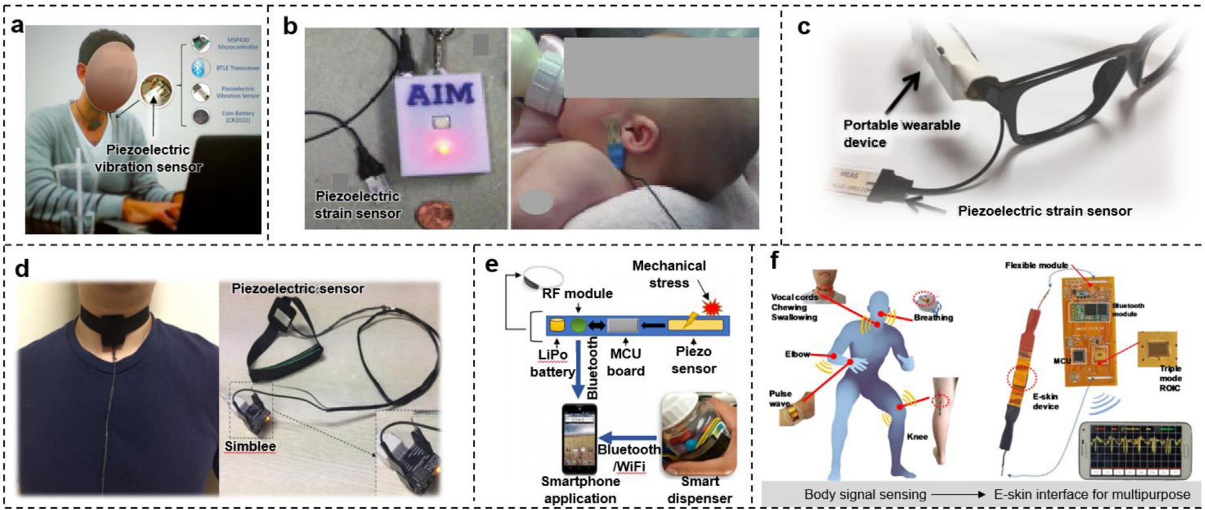

Fig. 21. Wearable PENG sensors based wireless devices for behavior recognition. (a) Recognition of nutrition intake using time-frequency decomposition in a wearable necklace. Printed with permission from Ref. [238]. Copyright 2015 IEEE. (b) Monitoring of infant feeding behavior. Printed with permission from Ref. [237]. Copyright 2015 Hindawi Publishing Corporation. (c) A novel wearable device for food intake and physical activity recognition. Printed with permission from Ref. [242]. Copyright 2016 MDPI. (d) Food intake detection and classification using a necklace-type piezoelectric wearable sensing system. Printed with permission from Ref. [241]. Copyright 2018 the Institute of Electronics, Information and Communication Engineers. (e) A wearable sensor system for medication adherence prediction. Printed with permission from Ref. [240]. Copyright 2016 Elsevier. (f) A Triple-mode flexible e-skin sensor interface. Printed with permission from Ref. [246]. Copyright 2017 MDPI.

achieved by an interlocked PVDF/RGO micro-dome array structure (Fig. 21f) [246]. A flexible system prototype is developed and provide various wireless wearable sensing functions—including pulse wave, voice, chewing/swallowing, breathing, knee movements, and temperature—while their real-time sensed data are displayed on a smartphone with Bluetooth transmission.

Wireless sensor network with TENG

Power transmission of TENGs for IoT sensory network

Similarly, vast amount of researches on TENG bring the feasibility to distributed wireless sensor network for IoT purpose, as the diverse and customizable devices demonstrate the abilities of converting different mechanical energy into electricity [282–285]. For the early stage studies, due to the relative low power density of TENG, the main direction of developing wireless sensor network is design the unique structure to harvest the ambient wasted energy efficiently, such as wind, water, and vibration *etc*., for powering the transmitter [67,286–288].

In Fig. 22a, Chen et al. presented TENG and EMG to fabricate a hybrid vibration energy harvester in order to power an active RFID tag. An all-in-one wearable system with power management module was demonstrated as embedded in shoes for enabling automatic long-distance identification of door access [289]. Zhang et al. has proposed a single-electrode cylindrical TENG for harvesting rotational energy induced by aerovane. The surface of triboelectric layer was etched for patterning with nanostructures to enhance the output up to 20 V under 300 RPM. Together with an integrated wind sensor, a self-powered meteorologic monitoring system was realized [290]. Similarly, to build up power a wireless traffic volume sensor as illustrated in Fig. 22b, a rotating-disk-based hybridized nanogenerator of EMG and TENG was reported to enable better performance of wind energy harvesting. The main functional parts consist of rotator with triboelectrification layer and four magnets, and the stator with another triboelectrification layer and four coils, the entire device can generator a peak power of 17.5 mW under 1000 RPM [291]. Meanwhile, a superhydrophobic surface TENG was presented, the device made of paralleled polyamide (PA) film and two superhydrophobic films, is able to harvest energy from all directions [292].

Furthermore, similar to the wireless charging technique, the TENG with the ability of transmitting energy and signal wirelessly are attracting attentions for achieving IoT network. Moving forward, several modified transmitters and collectors were also proposed [293]. In Fig. 22c, Jie et al. has reported rotational TENG which was combined by the contact-type TENG and the disconnect-type TENG. In addition, the ferroalloy collectors with bar array structure are designed to wirelessly deliver energy using the Maxwell's displacement current from the disconnect-type TENG which is 2 cm below the collectors. A maximum power density of 21.8 mW/m^2 can be obtained, and the delivery distance, size, as well as the receiving location of collectors, are the key factors for good efficiency [294]. As shown in Fig. 22d, the TENG consists of a Teflon film and a 3D-printed graphene polylactic acid (gPLA) nanocomposite on a polyimide film is integrated with the coils designed for wireless transmission. The primary test indicated that a 1 μF capacitor can be charged wirelessly to 5.0 V in 1 min by hand tapping [295]. As depicted in Fig. 22e, a wireless transmission energy source made by rotating-disk-based electromagnetic (EMG)–triboelectric hybrid energy harvester was developed by Chen et al. Because EMG and TENG has higher output current and voltage respectively, the energy generation performance can be improved for wireless transmission since the current determines the charging rate of capacitors and the voltage determines the final chargeable voltage. It is also observed that, by connecting the absorbing mediums to the ground, an ambient electromagnetic wave can induce an electrostatic signal to amplify this induction effect. In general, the delivered voltage from the receiver can reach 153 V at a distance of 80 cm [296]. Moreover, by converting the alternating current to continuous direct current, Zhu et al. developed the dual-intersection TENGs to power the electronics directly and effectively [297].

Moreover, similar to those piezoelectric ultrasonic transducers, the attempt of using TENG to receive the power via acoustic wave has been conducted occasionally, for the conditions with the solid barriers. Liu et al. reported a TENG for receiving the vibrational energy delivered through any solid material wirelessly, as depicted in Fig. 22f. By using a bass resonator as a mechanical power source, the proposed TENG can charge a commercial capacitor up to 10 V in 33–86 s, and the charging performance was affected by different solid medium [298].

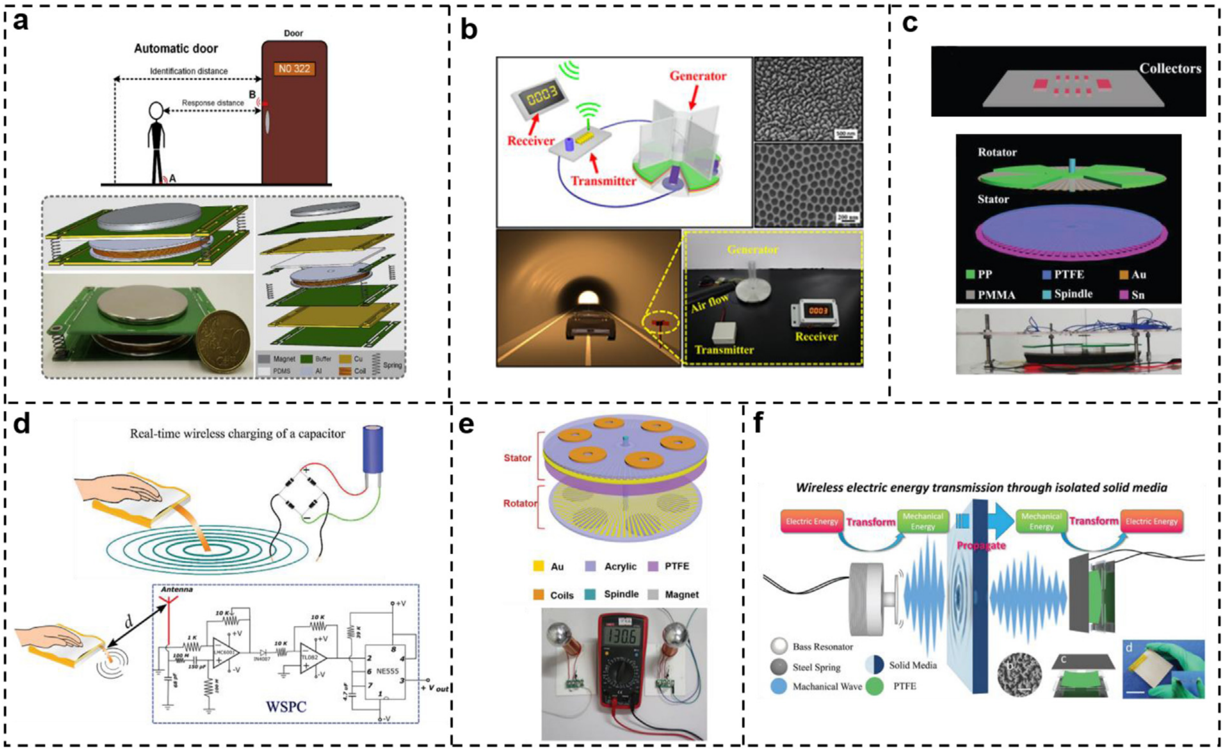

Fig. 22. Direct and wireless power transmission of TENGs for supporting the IoT sensor network. (a) Active RFID tag integrated with wearable hybrid nanogenerator. Printed with permission from Ref. [289]. Copyright 2019, Elsevier. (b) Rotating-disk-based hybridized EMG-TENG for wireless sensor node. Printed with permission from Ref. [291]. Copyright 2016, American Chemical Society. (c) Power delivery by a rotating TENG via wireless transmissions using maxwell's displacement currents. Printed with permission from Ref. [294]. Copyright 2018, John Wiley & Sons. (d) A wireless triboelectric nanogenerator. Printed with permission from Ref. [295]. Copyright 2015, American Chemical Society. (e) Coil-based wireless power transmission by EMG-TENG. Printed with permission from Ref. [296]. Copyright 2019, The Royal Society of Chemistry. (f) Wireless energy transmission through isolated solid media. Printed with permission from Ref. [298]. Copyright 2018, John Wiley & Sons.

Wireless transmission with wireless modules

The working mechanism of the triboelectric effect indicates a pulse-like waveform generated by the external stimuli. This waveform can be further tuned by modifying the design of TENG devices for the particular requirements, so that the signal can contain more information. In order to ensure the data quality and the transmission range, a considerable amount of current researches are utilizing the commercial Bluetooth and Wi-Fi module with low power consumption version to send the triboelectric signals wirelessly. In Fig. 23a, Qiu et al. developed a TENG based control disk interface which can generate 3-bit binary-reflected Gray-code (BRGC) by sliding across the modified electrodes. The hybridized power generation from TENG and solar cell can support the external circuit for conducting smart home applications [32]. Based on the introduction of new materials and the new bio-inspired concept, Zou et al. presented a bionic stretchable nanogenerator (BSNG) by mimicking the ion channel structure on the cytomembrane of electrolyte in electric eel, as illustrated in Fig. 23b [299]. This device can generate 10 V of open-circuit voltage in liquid solution, which gives the possibility of applying TENG for underwater energy harvesting and sensing. With the integrated wireless module, the human motion during swimming can be monitored and identified for training and safety purpose via a wireless protocol.

Recently, the coil-based transmission technique is also showing the capability of transmitting the sensing signal wirelessly and directly. A self-power-transmission and non-contact-reception keyboard with resonant TENG was developed by Yin et al., as illustrated in Fig. 23c. The external capacitor can alter the characteristic resonant frequency of triboelectric output, and hence, each coil under the button is integrated with an external capacitor to form an LC circuit for generating oscillating signals that can be coupled to a receiving coil, so that the corresponding key information can be defined via frequency [300]. However, the transmission range is limited at the current stage.

Wireless transmission via optical and acoustic approaches

As mentioned before, the signal waveforms of TENG based sensors carry the specific information. Hence, by converting those electrical signals into the other types of signals, the corresponding data can then be transmitted via other wireless approaches, such as the laser diode and the acoustic waveforms. In Fig. 24a, Chen et al. proposed a wireless sensing system that consists of a TENG integrated with a microswitch, an LC resonant circuit, and a coupling inductor. A red laser and a photodetector are applied as the transmitter and receiver for delivering the sensing information wirelessly with identity. The external capacitors are used as identity capacitors as well [301]. Moreover, in another demonstration of optical wireless transmission of identities without the external capacitors shown in Fig. 24b. Each elastomer-based key on the keyboard possesses the good selectivity of output signals to compare to other keys. The microcontrollers can then assist in lighting up an infrared LED with distinct signals from each key during pressing, and the detector identifies the delivered signals corresponding to the pressed keys [302]. Furthermore, a universal and arbitrary tactile interactive system was reported by applying various triboelectric materials and working modes to detect different human motions (Fig. 24c). To achieve the wireless signal transmission, an optical communicator composed of a LED and a photoresistor driven by TENG is integrated, and can improve the irregular triboelectric signals for stable communication [303]. Additionally, the aforementioned eye motion sensors are also considered as an appropriate research direction for supporting users with limb disabilities to operate those IoT appliances [31,259].

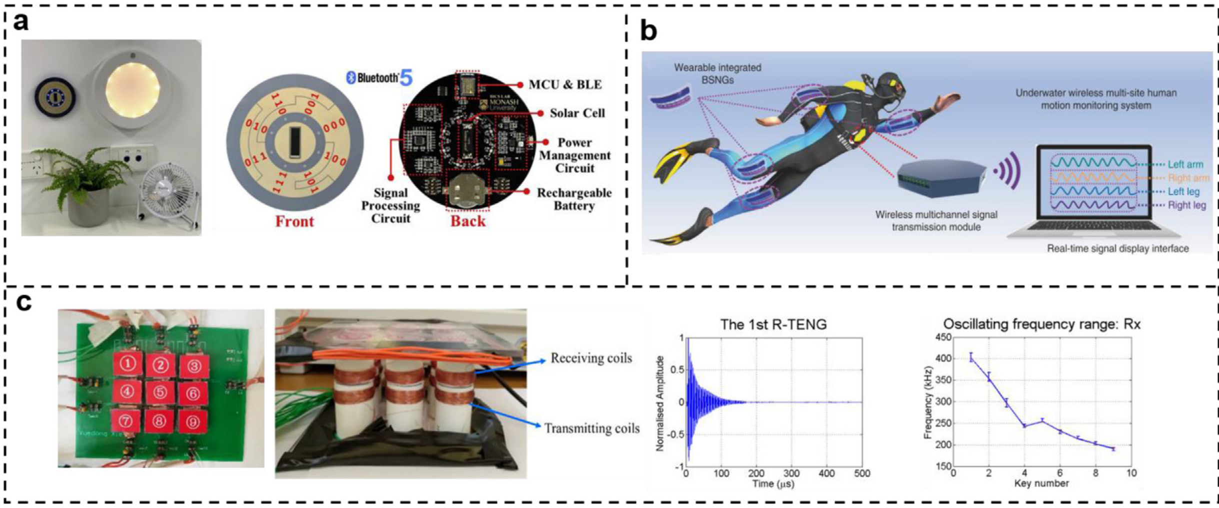

Fig. 23. Transmission of TENG based sensory information for the applications of IoT network with wireless modules and coils. (a) Gray code control interface for IoT smart home. Printed with permission from Ref. [32]. Copyright 2020, Elsevier. (b) A bionic TENG for underwater sensing and energy harvesting. Printed with permission from Ref. [299]. Copyright 2019, Springer Nature Limited. (c) Non-contact-reception keyboard based on a resonant TENG (R-TENG). Printed with permission from Ref. [300]. Copyright 2018, Elsevier.

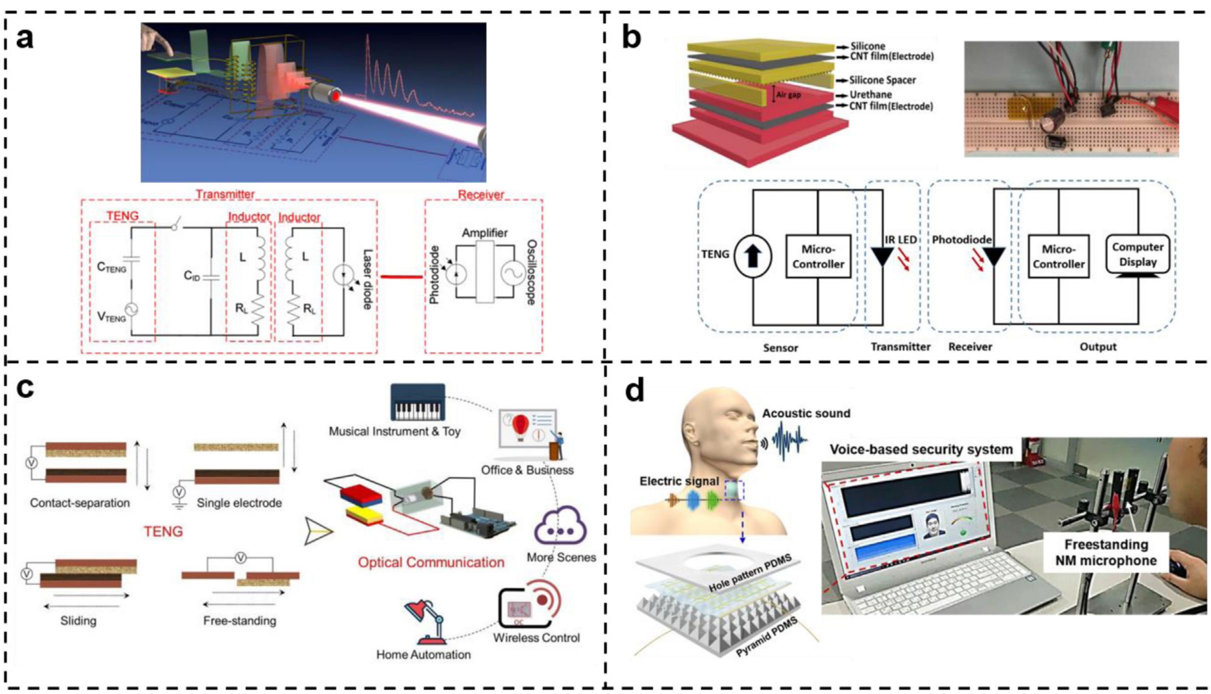

Fig. 24. Wireless transmission of TENG based sensory information for the applications of IoT network with optical and acoustic approaches. (a) Instantaneous self-powered laser based wireless sensing with self-determined identity. Printed with permission from Ref. [301]. Copyright 2018, Elsevier. b) Washable TENG with LED for wireless communications and soft robotics pressure sensor arrays. Printed with permission from Ref. [302]. Copyright 2017, Elsevier. (c) A universal interactive system using optical communication. Printed with permission from Ref. [303]. Copyright 2020, Elsevier. (d) Conductive nanomembranes for skin-attachable loudspeakers and microphones. Printed with permission from Ref. [304]. Copyright 2018, American Association for the Advancement of Science.

On the other hand, the vibration caused by acoustic waves also can be used for making TENG based voice recognition. As shown in Fig. 24d, a TENG microphone consists of nanomembranes made by orthogonal Ag nanowire arrays and PDMS pyramid layer was proposed by Kang et al. [304]. By placing the device on throat, the acoustic waveform of the output voltage and the corresponding spectrograms can be obtained via triboelectric signals. Hence, the analysis of frequency pattern can realize the identification of voiceprint, which can contribute to the wireless authorization of access for IoT scenarios.

Hybridized nanogenerators and self-sustained systems

Consequently, to further improve the sustainability of those wireless network, the output performance is the key indicator need to be considered in order to ensure the feasibility of practical application, such as the continuous operation of multiple electronics, and the power required for wireless transmission of IoT sensory systems. This issue becomes even severe in terms of wearable nanogenerators, due to the restriction of scalability.

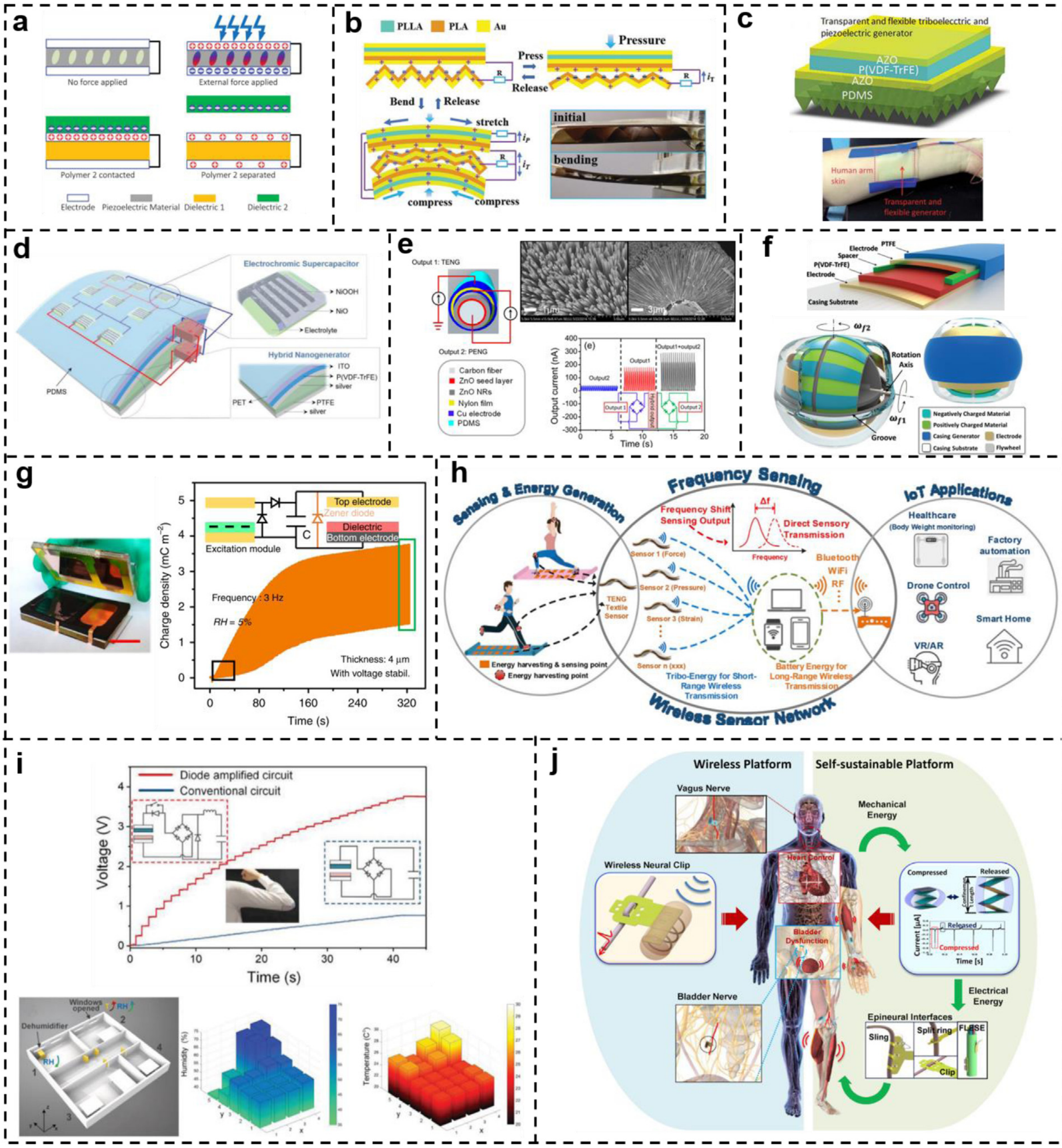

Fig. 25. PENGs/TENGs hybridized nanogenerators and other power boosting strategies for achieving the self-sustained systems. (a) Theoretical analysis and experimental verification of coupling of piezoelectric and triboelectric effects. Printed with permission from Ref. [305]. Copyright 2015, John Wiley & Sons. (b) Poly (lactic acid)-based hybrid PENG and TENG. Printed with permission from Ref. [155]. Copyright 2020, John Wiley & Sons. (c) A transparent and biocompatible hybrid nanogenerator and body movement sensor. Printed with permission from Ref. [307]. Copyright 2017, The Royal Society of Chemistry. (d) PENG/TENG-driven electrochromic supercapacitor power package. Printed with permission from Ref. [308]. Copyright 2018, John Wiley & Sons. (e) 3D fiber-based hybrid nanogenerator for energy harvesting. Printed with permission from Ref. [249]. Copyright 2014, American Chemical Society. (f) Hand-driven gyroscopic hybrid nanogenerator. Printed with permission from Ref. [310]. Copyright 2018, John Wiley & Sons. (g) Maximization of charge density by quantifying the air-breakdown of charge-excitation for TENG. Printed with permission from Ref. [315]. Copyright 2020, Springer Nature. (h) Battery-free short-range wireless sensor network using TENG based direct sensory transmission. Printed with permission from Ref. [316]. Copyright 2020, Elsevier. (i) Self-sustainable wearable textile-based sensory system. Printed with permission from Ref. [59]. Copyright 2019, John Wiley & Sons. (j) Advanced neural interfaces for the peripheral nervous system and future applications. Printed with permission from Ref. [317]. Copyright 2018, Elsevier.

PENG and TENG hybridized nanogenerators

The sensitivity and sensing range of those nanogenerator based self-powered sensors are also limited. The individual function of either PENG or TENG may not have enough output and adaptability for various scenarios. As a result, the hybrid devices consist of both PENG and TENG are reported frequently as they usually possess the similar compact structure for specific mechanical stimuli, which is convenient for the facile integration. Importantly, other than ceramics, several polymer-based piezoelectric materials also show good flexibility that is compatible with wearable TENGs, such as PVDF. In Fig. 25a, Han et al. has systematically studied the coupling of piezoelectric and triboelectric effects at different connections, the relationship between piezoelectric polarization and triboelectric charge density, and the influence on electrical parameters [305]. The study revealed that the output performance of hybrid nanogenerator has strong dependency on these factors.

Hence, the multi-level output and the amplification/degradation of output would be controllable. In general, this research offers a guideline of designing the favorable hybrid nanogenerator and self-powered sensors which can improve the effectiveness and functionalities as wearable devices. A biocompatible Poly(lactic acid) (PLA) material and poly(L-lactic acid) (PLLA) were utilized to fabricate the TENG and PENG respectively, for e-skin based HMI (Fig. 25b) [155]. The unimorph PENG and triangular waveform TENG were hot pressed to form a hybrid nanogenerator. The open circuit voltage and short circuit current reached 35 V and 1 μA with elbow bending. Wang et al. has developed a hybrid nanogenerator with P(VDF-TrFE) nanofibers and Polydimethylsiloxance /multi-wall carbon nanotubes (PDMS/MWCNT) [306]. The micropatterned PDMS with MWCNT dopant can improve the triboelectric output and the initial capacitance. The device has a power density of 1.98 mW/cm^3 under the pressure force of 5 N. In addition, by applying Al:ZnO (AZO) as electrodes, a transparent and flexible hybrid nanogenerator was fabricated as illustrate in Fig. 25c [307], which can be used as e-skin for monitoring body motions. A power density of 751.1 mW/m^2 was achieved with 200 μm. Moreover, the power storage solution is another essential aspect for real applications. In Fig. 25d, Qin et al. has presented a piezoelectric/triboelectric hybrid nanogenerator integrated with electrochromic supercapacitors to build up a self-charging power package [308]. P(VDF-TrFE) and PTFE films were used as piezoelectric and triboelectric materials respectively. The supercapacitor had a stable cycling performance with 80.7 % remaining capacitance after 10,000 cycles. The NiOOH and NiO with reversible Faradaic redox process of Ni^{2+}/Ni^{3+} couple can exhibit different colors at varied electrical potentials to indicate the charging state. He et al. reported a paper-based piezoelectric/triboelectric hybrid nanogenerator with ITO and PVDF, and a paper-based supercapacitor composed of a-CNF (activated carbon nanofibers)/polymer electrodes and H_3PO_4/PVA gel electrolyte [309]. Meanwhile, ZnO nanowire/nanorod as another well-known piezoelectric material, is also studied to develop flexible hybrid nanogenerators. In Fig. 25e, Li et al. has fabricated 3D fiber-based hybrid nanogenerator using ZnO nanorod grown on the carbon fiber as PENG, and Nylon film/Cu surrounded on this fiber as TENG for pressure sensing. The elbow bending angle can be monitored. As a fabric based nanogenerator, the power density for TENG and PENG achieved 42.6 mW/m^2 and 10.2 mW/m^2 respectively [249]. In Fig. 25f, a hand-driven gyroscopic hybrid nanogenerator ball was proposed by Chung et al. for charging portable devices [310]. The alternating patterned TENG on the core flywheel, the TENG and P(VDF-TrFE) based PENG on the case can harvest the mechanical energy from hand gripping, rotation, centrifugal force, and vibration simultaneously. The open circuit voltage and short circuit current reached 90 V and 11 μA at 200 Hz respectively. On the other hand, a smart sock with PENG and TENG was presented by Zhu et al. This sock consists of PZT ceramic chips as PENG embedded in TENG cotton sock which was coated by PEDOT:PSS conductive solution. Except the standard power generation function, the segmental design of PENG and TENG units allowed the detection of gait, pressure and walking direction. By leveraging the different responses of PENG and TENG to the humidity influence, the sensor fusion concept enabled the monitoring of sweat level of user [137].

Self-sustained systems with boosted output performance

Except the hybridized devices of PENG and TENG, there are other approaches have been adopted to facilitate the complete self-sustained IoT sensory system [311–313]. One of the major efforts is to study the effective approaches for boosting up the charge density of TENGs [314]. By applying a LC oscillating circuit which consists of diode, switch, and inductor, Xu et al. has demonstrated a strategy of flipping the free charges on the conductive layer in each cycle, in order to accumulate those charges [312]. As illustrated in Fig. 25g, a systematic evaluation of the contact efficiency and air breakdown model was reported by Liu et al. Based on Paschen's law, a high charge density can be achieved by tuning the different parameters, including the thickness of dielectric layers, the external capacitor, the atmospheric environment, and surface contact completeness. As a result, a charge density up of 2.38 mC/m^2 was obtained with 4 μm PEI film and carbon/silicone electrode at 5 % relative humidity [315].

In Fig. 25h, Wen et al. has presented a fabric based TENG sensor with superhydrophobic coating which was suitable for HMI using direct wireless sensory transmission. A diode was introduced to boost the output for improving the wireless transmission performance. The oscillation frequency response against the applied force was utilized to achieve static force sensing. In addition, with the aid of the external capacitor, a multi pixel wireless control system was demonstrated [316]. Similarly, the textile-based TENG integrated on clothes can successfully support the energy consumption of humidity and temperature sensors in IoT module for periodic detection of the environmental data. Thus, by connecting with cloud server, the demonstration of a self-sustainable sensor network for indoor scenario was realized, as illustrated in Fig. 25i [59]. Moving towards, as shown in Fig. 25j, the next breakthrough of implantable nanogenerators may enable the in-vivo self-powered IoT sensory system not only for the pacemaker or monitoring devices, but also for those neural interfaces to assist the patient in restoring partial functions via peripheral nervous system, such as controlling the bladder contraction or the sciatic nerve [317].

In general, both PENG and TENG are experiencing the burgeoning in the recent years (Fig. 26). As two of the most promising and diversified techniques for harvesting mechanical energy to be the sustainable power source or self-powered sensor, there are a considerable amount of wearable and implantable applications can be achieved as shown in the milestones. In terms of a prospective view, except the continuous researches on the improvement of the performance of PENG and TENG, we also need to consider the system integration of these distributed devices via wireless communication, so that the body sensor network or IoT sensory network as the practical applications can be realized. Hence, the continuous studies on wireless signal and energy transmission become essential to overcome the obstacle of implementing the IoT sensor network for better user experiences.

Evaluations of PENG and TENG devices

Based on these researches which cover the various application fields, PENG and TENG reveal their potentials of being the effective machinal transducers for harvesting energy and sensing. Two mechanisms are sharing some common properties, but also possessing the individual uniqueness in specific scenarios (Table 3).

Comparisons between PENG and TENG devices

For common properties, both of PENG and TENG are originally generating the AC based electrical outputs, and having the similar level of impedances. This kind of signals can benefit the sensing functions by differentiating the bi-directional mechanical stimulus with the positive and the negative signal peaks. However, AC output is not favorable for energy harvesting during the charging of capacitor in power management unit. To solve this issue, full bridge rectifier is one of the most commonly used approach [318]. Additionally, several easier or more efficient power boosting strategies were developed in recent years, especially for TENGs [319]. For instance, in terms of power management, an inductor-free output multiplier based on bennet's doubler effect was presented [320], and a fractal-design based switched-capacitor-convertor

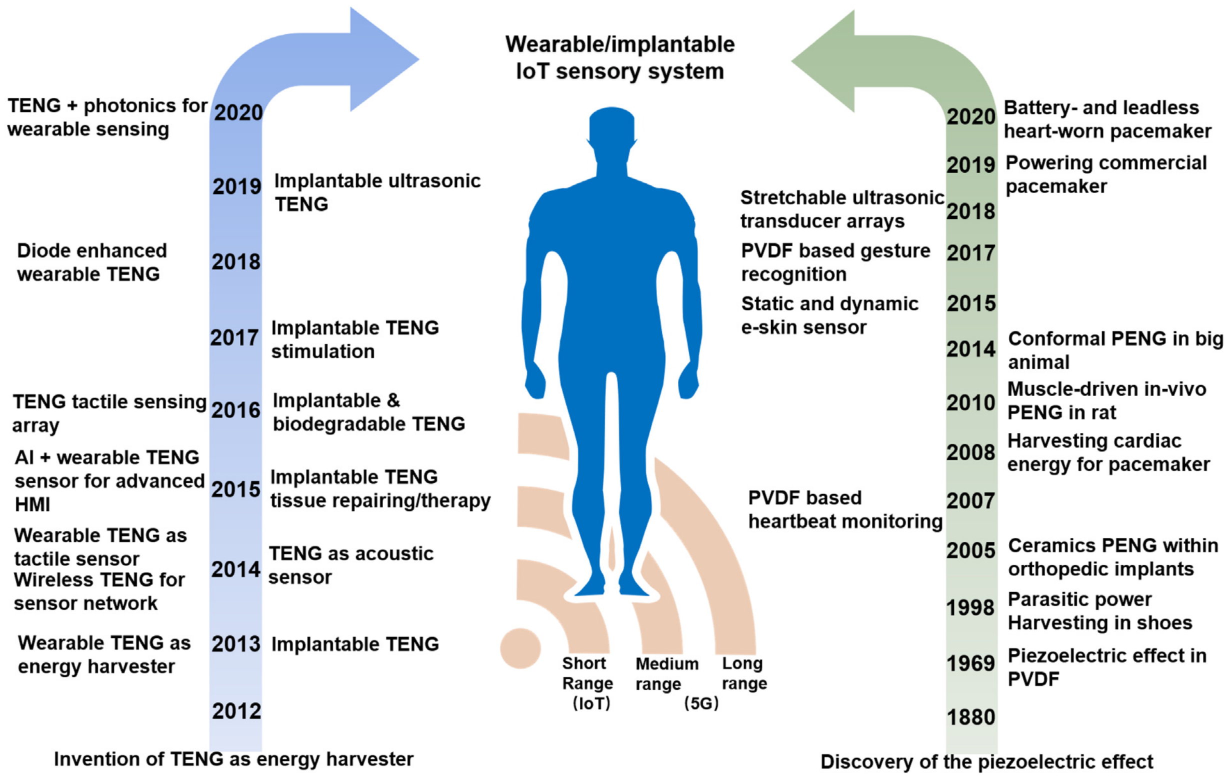

Fig. 26. Milestones of PENG and TENG based devices for establishing wearable and implantable IoT sensory system.

Table 3
Comparisons between PENG and TENG.

	PENG	TENG
Materials and Fabrication	• Commercialized technique • Compatible with MEMS process • Relative complex and expensive process • Ceramics are fragile	• Wide options of materials • Relative cheap for most of materials • Easy to fabricate
Power density	• High power density • Affected by operation frequency	• Relative low power density, but highly tunable with surface texturing and charge implantation, *etc.* • Multiple operation mode
Sensing (sensitivity, sensing range, response time)	• Suitable for high dynamic sensing • Fast response • Poor static sensing	• Wide sensing range (depend on materials and design) • Good dynamic sensing • Fast response • Poor static sensing
Scalability	• Suitable for miniaturization • Expensive and fragile for large size applications	• Suitable for large-area applications • Low output after miniaturization
Stability	• Good electrical stability • Poor mechanical stability	• Sensitive to environmental fluctuation, i.e., humidity. • Good mechanical stability (depend on materials and design)
Biocompatibility	• Polymer and lead-free materials are biocompatible. • Lead-based ceramics need encapsulation.	• Many polymer materials are biocompatible • Able to apply the biocompatible materials to fabricate TENG directly

was developed to achieve high energy transfer efficiency [321]. A self-doubled-rectification was also proposed for alternating the TENG outputs into two periods with different output directions [322]. Moreover, Liu et al. reported a system of external charge excitation and self-charge excitation with voltage-multiplying circuits for a high and stable power output [314].

On the other hand, there are many differences between PENG and TENG, including materials, fabrication process, cost, power density, *etc.* For PENGs, there are still only a few choices available. Most of them are ceramics, such as PZT, PMN-PT, BTO, ZnO, AlN, *etc.* These materials usually require relative complex fabrication process, such as sintering and polarization, to obtain the desirable piezoelectric properties, and the unit cost is eventually higher than TENGs. The ceramic based piezoelectric materials experience the brittle issue as well. Therefore, the thinning or fiber related process are commonly applied in response to the requirements of mechanical durability in the wearable or implantable purposes, and they are usually incorporated with other metallic or polymer substrates.

The high-power density can be considered as a great advantage of many PENGs. Thus, PENGs and PENG-based sensors are preferred in those space sensitive scenarios, such as implantable devices, and non-cloth based miniaturized wearable devices [323]. But some of them may need encapsulation due to the presence of lead.

For TENGs, there are almost unlimited candidates of materials due to the nature of triboelectric effect [324]. Hence, the cost effectiveness and the compatibility are the most important features, especially when considering the large area usage on human body. Although many TENGs do not provide the power density as high as PENGs, the increasing of functional area can greatly compensate this drawback. Noticeably, unlike PENGs, the working principle of TENG indicates its vulnerability to the influence of moisture. However, the requirement of the additional space for interaction of two triboelectric materials brings the challenges to the encapsulation, especially for implantable devices.

Reliability of PENG and TENG devices

As the transducers that convert the mechanical energy into electrical energy, both PENG and TENG devices are encountered with various external forces and harsh environment. Hence, the cyclic deformation and the well encapsulation are the great challenges to the robustness of these devices, especially for the implantable devices.

Comparing to TENGs, PENGs performs poor mechanical stability due to the fragile piezoelectric layer. Therefore, researchers need to consider the maximum deformation for practical applications to design the device structure. Some strategies will be very necessary to limit the deformation for keeping the good mechanical stability, including the stopper, and the damper. To avoid the corrosion from environment, different encapsulation techniques are adopted in those implantable devices. PENGs usually do not require the internal space for interactions, and hence, the encapsulation becomes easier.

Currently, based on the available data of the reliability tests, TENG devices usually can experience over thousands to millions of cyclic impacts without the significant failure of the structures or decay of the output performance. There is still limited information about the actual life-time of those TENGs. The relatively low cost of replacement may partially overcome this issue. Besides, the advancement of self-healing materials seems to be another promising solution for extending the service time of some elastomer-based devices. On the other hand, the extra space for sliding or separation is challenging in making a good encapsulation for harsh environment. Some of the output performance are usually sacrificed as a compromise. Hence, the advanced encapsulation technique and the narrow space TENGs with excellent output performance are worth for further researches.

In general, by considering the respective advantages and disadvantages of PENG and TENG, these two techniques can be considered as complementary parts of each other, ranging from the large area to small area energy harvesting and sensing. Hence, by observing the differences of categories for PENG and TENG related researches listed in each section, the concentrations of each mechanism and the connections between them can be understood. As a prospect, the fusion of two devices will increase the functionalities and enhances the general performance.

Concluding remarks and outlook

In general, we provide a thorough introduction about the recent advancement of wearable and implantable devices using triboelectric and piezoelectric mechanisms for implementing the IoT sensor network. Both of the two effects share several similarities in terms of nanogenerators and self-powered sensors, such as the responses to mechanical stimuli, the output signals, and the capability of compact design.

In terms of nanogenerator as a power supply, the development of PENG greatly relies on the improvements of the piezoelectric materials or advanced micromachining processes. As to wearable PENGs on the human body, the main development tendency includes high output power, flexibility, no irritation to the skin for practical feasibility. On the basis of abundant available kinetic energy on the human body these energies, the reported researches of wearable PENGs focus on several main body parts, such as hand, wrist, and joint, as well as the wearable objects, such as clothes, backpack, glove, and shoes. Meanwhile, TENG as an emerging technology exhibits a promising future of smart and comfortable wearables due to its low cost and numerous candidates of materials. Different operation modes are utilized with respect to various human motions. In the early stage, the majority of researches applied flexible or stretchable triboelectric materials as an attachment on cloth or skin for harvesting mechanical energy. By leveraging the advantages of clothes, the textile-based TENG acquires the great attention recently, such as the fabrication of new TENG textile, the functional coating on conventional textile. Moving forward, the diversified designs, for instance, insole, sock, and wrist band, *etc*., were proposed with the capability of generating mW level of power.

Besides, to maintain long-term normal working of the medical devices, there are urgent demands for implantable nanogenerators. Miniaturization, biocompatibility and flexibility are the essential requirements worth for continuous development. The researches on practical applications greatly promote the advancement of implantable PENGs. But the long-term output stability and safety in vivo are the next-step challenges. In addition, the introduction of biocompatible and biodegradable materials also brings TENG into the implantable devices, not only for serving as power supply, but also for exploring the abilities to facilitate the medical therapy and conducting the neural stimulation.

Meanwhile, as a concept of self-powered sensor, PENG sensors for the human body are to monitor the vital signs for healthcare and to get the motion information for posture recognition. TENG with various designs specialized in sensing the corresponding motions were developed, including the microstructure pattern, grid electrodes, arch or wrinkle shape, and thin membrane, *etc*. Hence, the tactile and even the voice information can be monitored for achieving human-machine interactions via the proper data processing. Deep learning algorithms, artificial neural network and other artificial intelligent methods are favorable and useful to do this, which also is promising to promote the practical applications of wearable PENG and TENG sensors.

On the other hand, to fully establish IoT sensory network, the relevant studies of wireless transmission supported by PENG and TENG are introduced as well. The frequently applied approach is to support the Bluetooth or WiFi module-based communication by nanogenerator together with the capacitor and power management unit. In the meantime, the attempts of bypassing those wireless modules become another tendency, such as the direct energy or signal transmission via coils in a short range, which reduces the complexity of electric units but also raises the issue of transmission efficiency. In the meantime, both of TENG and PENG are experiencing several common or individual challenges, including (1) wearing comfortability; (2) frequency dependence of the output power for human motion; (3) stability for those fragile piezoelectric ceramics under movement; (4) sufficient output power for wearable electronics; (3) high sensitivity, (6) signal processing for high accuracy in monitoring. Noticeably, owing to the similar operation mechanism, the hybridized devices of PENG and TENG can act as a solution to some of the above issues. Their complementary functions to each other assist in the improvement of power density, sensitivity, sensible parameter, and stability, *etc*.

To summarize, the current advancement of PENG and TENG shed light on the feasibility of digitized and distributed systems composed of wearable and implantable devices, which are featured with self-powering, intimate and multi-dimensional sensing, and wireless. Further researches will make these self-sustained smart systems serve our life better, such as healthcare, entertainment, and productivity.

Author contributions

Minglu Zhu: Conceptualization, Writing - original draft, Writing - review & editing. **Zhiran Yi:** Conceptualization, Writing - original draft, Writing - review & editing. **Bin Yang:** Writing - review & editing, Supervision, Funding acquisition. **Chengkuo Lee:** Conceptualization, Supervision, Investigation, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

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

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References

[1] Q. Shi, B. Dong, T. He, Z. Sun, J. Zhu, Z. Zhang, C. Lee, Progress in wearable electronics/photonics—moving toward the era of artificial intelligence and internet of things, InfoMat (2020) 12122, http://dx.doi.org/10.1002/inf2.12122 (in press), inf2.
[2] X. Tang, X. Wang, R. Cattley, F. Gu, Energy Harvesting Technologies for Achieving Self-Powered Wireless Sensor Networks in Machine Condition Monitoring : A Review, 2018, http://dx.doi.org/10.3390/s18124113.
[3] L. Liu, Q. Shi, J.S. Ho, C. Lee, Study of thin film blue energy harvester based on triboelectric nanogenerator and seashore IoT applications, Nano Energy 66 (2019) 104167, http://dx.doi.org/10.1016/j.nanoen.2019.104167.
[4] J. Qi, P. Yang, A. Waraich, Z. Deng, Y. Zhao, Y. Yang, Examining sensor-based physical activity recognition and monitoring for healthcare using Internet of Things : a systematic review, J. Biomed. Inform. 87 (2018) 138–153, http://dx.doi.org/10.1016/j.jbi.2018.09.002.
[5] C. Wang, L. Dong, D. Peng, C. Pan, Tactile sensors for advanced intelligent systems, Adv. Intell. Syst. 1900090 (2019) 1900090, http://dx.doi.org/10.1002/aisy.201900090.
[6] T. Jiang, L.M. Zhang, X. Chen, C.B. Han, W. Tang, C. Zhang, L. Xu, Z.L. Wang, Structural optimization of triboelectric nanogenerator for harvesting water wave energy, ACS Nano 9 (2015) 12562–12572, http://dx.doi.org/10.1021/acsnano.5b06372.
[7] H. Tai, S. Wang, Z. Duan, Y. Jiang, Evolution of breath analysis based on humidity and gas sensors: potential and challenges, Sensors Actuators B Chem. 318 (2020) 128104, http://dx.doi.org/10.1016/j.snb.2020.128104.
[8] F. Wen, T. He, H. Liu, H.-Y. Chen, T. Zhang, C. Lee, Advances in chemical sensing technology for enabling the next-generation self-sustainable integrated wearable system in the IoT era, Nano Energy 78 (2020) 105155, http://dx.doi.org/10.1016/j.nanoen.2020.105155.
[9] M. Zhu, T. He, C. Lee, Technologies toward next generation human machine interfaces: from machine learning enhanced tactile sensing to neuromorphic sensory systems, Appl. Phys. Rev. 7 (2020), 031305, http://dx.doi.org/10.1063/5.0016485.
[10] D. Jiang, B. Shi, H. Ouyang, Y. Fan, Z.L. Wang, Z. Li, Emerging implantable energy harvesters and self-powered implantable medical electronics, ACS Nano 14 (2020) 6436–6448, http://dx.doi.org/10.1021/acsnano.9b08268.
[11] D. Jiang, B. Shi, H. Ouyang, Y. Fan, Z.L. Wang, Z.M. Chen, Z. Li, A 25-year bibliometric study of implantable energy harvesters and self-powered implantable medical electronics researches, Mater. Today Energy. 16 (2020) 100386, http://dx.doi.org/10.1016/j.mtener.2020.100386.
[12] L. Liu, Q. Shi, C. Lee, A novel hybridized blue energy harvester aiming at all-weather IoT applications, Nano Energy 76 (2020) 105052, http://dx.doi.org/10.1016/j.nanoen.2020.105052.
[13] H. Wang, J. Zhu, T. He, Z. Zhang, C. Lee, Programmed-triboelectric nanogenerators—a multi-switch regulation methodology for energy manipulation, Nano Energy 78 (2020) 105241, http://dx.doi.org/10.1016/j.nanoen.2020.105241.
[14] Y. Wang, H. Wu, L. Xu, H. Zhang, Y. Yang, Z.L. Wang, Hierarchically patterned self-powered sensors for multifunctional tactile sensing, Sci. Adv. 6 (2020) eabb9083, http://dx.doi.org/10.1126/sciadv.abb9083.
[15] Q. Shi, Z. Zhang, T. He, Z. Sun, B. Wang, Y. Feng, X. Shan, B. Salam, C. Lee, Deep learning enabled smart mats as a scalable floor monitoring system, Nat. Commun. 11 (2020) 4609, http://dx.doi.org/10.1038/s41467-020-18471-z.
[16] F. Arab Hassani, R.P. Mogan, G.G.L. Gammad, H. Wang, S.-C. Yen, N.V. Thakor, C. Lee, Toward self-control systems for neurogenic underactive bladder: a triboelectric nanogenerator sensor integrated with a bistable micro-actuator, ACS Nano 12 (2018) 3487–3501, http://dx.doi.org/10.1021/acsnano.8b00303.
[17] J. Wang, H. Wang, T. He, B. He, N.V. Thakor, C. Lee, Investigation of low-current direct stimulation for rehabilitation treatment related to muscle function loss using self-powered TENG system, Adv. Sci. 6 (2019) 1900149, http://dx.doi.org/10.1002/advs.201900149.
[18] H. Wang, J. Wang, T. He, Z. Li, C. Lee, Direct muscle stimulation using diode-amplified triboelectric nanogenerators (TENGs), Nano Energy 63 (2019) 103844, http://dx.doi.org/10.1016/j.nanoen.2019.06.040.
[19] J. Wang, H. Wang, N.V. Thakor, C. Lee, Self-powered direct muscle stimulation using a triboelectric nanogenerator (TENG) integrated with a flexible multiple-channel intramuscular electrode, ACS Nano 13 (2019) 3589–3599, http://dx.doi.org/10.1021/acsnano.9b00140.
[20] Z. Li, Q. Zheng, Z.L. Wang, Z. Li, Nanogenerator-based self-powered sensors for wearable and implantable electronics, Research 2020 (2020) 1–25, http://dx.doi.org/10.34133/2020/8710686.
[21] S. Liu, H. Wang, T. He, S. Dong, C. Lee, Switchable textile-triboelectric nanogenerators (S-TENGs) for continuous profile sensing application without environmental interferences, Nano Energy 69 (2020) 104462, http://dx.doi.org/10.1016/j.nanoen.2020.104462.
[22] S. Nayak, Y. Li, W. Tay, E. Zamburg, D. Singh, C. Lee, S.J.A. Koh, P. Chia, A.V.Y. Thean, Liquid-metal-elastomer foam for moldable multi-functional triboelectric energy harvesting and force sensing, Nano Energy 64 (2019) 103912, http://dx.doi.org/10.1016/j.nanoen.2019.103912.
[23] T. Chen, Q. Shi, Z. Yang, J. Liu, H. Liu, L. Sun, C. Lee, A self-powered six-axis tactile sensor by using triboelectric mechanism, Nanomaterials. 8 (2018) 503, http://dx.doi.org/10.3390/nano8070503.
[24] H. Wu, Q. Shi, F. Wang, A.V.-Y. Thean, C. Lee, Self-powered cursor using a triboelectric mechanism, Small Methods 2 (2018) 1800078, http://dx.doi.org/10.1002/smtd.201800078.
[25] T. He, Z. Sun, Q. Shi, M. Zhu, D.V. Anaya, M. Xu, T. Chen, M.R. Yuce, A.V.Y. Thean, C. Lee, Self-powered glove-based intuitive interface for diversified control applications in real/cyber space, Nano Energy 58 (2019) 641–651, http://dx.doi.org/10.1016/j.nanoen.2019.01.091.
[26] S. Chen, K. Jiang, Z. Lou, D. Chen, G. Shen, Recent developments in graphene-based tactile sensors and E-skins, Adv. Mater. Technol. 3 (2018) 1–26, http://dx.doi.org/10.1002/admt.201700248.
[27] Y. Liu, R. Bao, J. Tao, J. Li, M. Dong, C. Pan, Recent progress in tactile sensors and their applications in intelligent systems, Sci. Bull. 65 (2020) 70–88, http://dx.doi.org/10.1016/j.scib.2019.10.021.
[28] C. Sun, Q. Shi, D. Hasan, M.S. Yazici, M. Zhu, Y. Ma, B. Dong, Y. Liu, C. Lee, Self-powered multifunctional monitoring system using hybrid integrated triboelectric nanogenerators and piezoelectric microsensors, Nano Energy 58 (2019) 612–623, http://dx.doi.org/10.1016/j.nanoen.2019.01.096.
[29] T. He, Q. Shi, H. Wang, F. Wen, T. Chen, J. Ouyang, C. Lee, Beyond energy harvesting - multi-functional triboelectric nanosensors on a textile, Nano Energy 57 (2019) 338–352, S221128551830939X.
[30] J. Zhu, X. Liu, Q. Shi, T. He, Z. Sun, X. Guo, W. Liu, O. Bin Sulaiman, B. Dong, C. Lee, Development Trends and Perspectives of Future Sensors and MEMS/NEMS, Micromachines 11 (1) (2019) 7, http://dx.doi.org/10.3390/mi11010007.
[31] D. Vera Anaya, T. He, C. Lee, M.R. Yuce, Self-powered eye motion sensor based on triboelectric interaction and near-field electrostatic induction for wearable assistive technologies, Nano Energy 72 (2020) 104675, http://dx.doi.org/10.1016/j.nanoen.2020.104675.
[32] C. Qiu, F. Wu, C. Lee, M.R. Yuce, Self-powered control interface based on gray code with hybrid triboelectric and photovoltaics energy harvesting for IoT smart home and access control applications, Nano Energy 70 (2020) 104456, http://dx.doi.org/10.1016/j.nanoen.2020.104456.
[33] C. Wenying, Y. Weidong, L. Zhaoling, Energy harvesting from human motions for wearable applications, in: Ind. Textila, 2018, pp. 390–393.
[34] P. Pillatsch, E.M. Yeatman, A.S. Holmes, A wearable piezoelectric rotational energy harvester, in: 2013 IEEE Int. Conf. Body Sens. Networks, IEEE, 2013, pp. 1–6, http://dx.doi.org/10.1109/BSN.2013.6575470.
[35] J. Kymissis, C. Kendall, J. Paradiso, N. Gershenfeld, Parasitic power harvesting in shoes, in: Dig. Pap. Second Int. Symp. Wearable Comput. (Cat.

No.98EX215), IEEE Comput. Soc, 1998, pp. 132–139, http://dx.doi.org/10.1109/ISWC.1998.729539.
[36] H. Liu, C. Lee, T. Kobayashi, C.J. Tay, C. Quan, Piezoelectric MEMS-based wideband energy harvesting systems using a frequency-up-conversion cantilever stopper, Sensors Actuators, A Phys. 186 (2012) 242–248, http://dx.doi.org/10.1016/j.sna.2012.01.033.
[37] T. Huang, S. Yang, P. He, J. Sun, S. Zhang, D. Li, Y. Meng, J. Zhou, H. Tang, J. Liang, G. Ding, X. Xie, Phase-separation-induced PVDF/Graphene coating on fabrics toward flexible piezoelectric sensors, ACS Appl. Mater. Interfaces 10 (2018) 30732–30740, http://dx.doi.org/10.1021/acsami.8b10552.
[38] J. Park, M. Kim, Y. Lee, H.S. Lee, H. Ko, Fingertip skin–inspired microstructured ferroelectric skins discriminate static/dynamic pressure and temperature stimuli, Sci. Adv. 1 (2015) e1500661, http://dx.doi.org/10.1126/sciadv.1500661.
[39] G. Zhu, R. Yang, S. Wang, Z.L. Wang, Flexible high-output nanogenerator based on lateral ZnO nanowire array, Nano Lett. 10 (2010) 3151–3155, http://dx.doi.org/10.1021/nl101973h.
[40] T.C. Hou, Y. Yang, H. Zhang, J. Chen, L.J. Chen, Z. Lin Wang, Triboelectric nanogenerator built inside shoe insole for harvesting walking energy, Nano Energy 2 (2013) 856–862, http://dx.doi.org/10.1016/j.nanoen.2013.03.001.
[41] F.A. Hassani, C. Lee, A triboelectric energy harvester using low-cost, flexible, and biocompatible ethylene vinyl acetate (EVA), J. Microelectromech. Syst. 24 (2015) 1338–1345, http://dx.doi.org/10.1109/JMEMS.2015.2403256.
[42] C. Zhang, T. Zhou, W. Tang, C. Han, L. Zhang, Z.L. Wang, Rotating-disk-based direct-current triboelectric nanogenerator, Adv. Energy Mater. 4 (2014) 1–7, http://dx.doi.org/10.1002/aenm.201301798.
[43] M. Shi, J. Zhang, H. Chen, M. Han, S.A. Shankaregowda, Z. Su, B. Meng, X. Cheng, H. Zhang, Self-powered analogue smart skin, ACS Nano 10 (2016) 4083–4091, http://dx.doi.org/10.1021/acsnano.5b07074.
[44] T. Zhou, C. Zhang, C.B. Han, F.R. Fan, W. Tang, Z.L. Wang, Woven structured triboelectric nanogenerator for wearable devices, ACS Appl. Mater. Interfaces 6 (2014) 14695–14701, http://dx.doi.org/10.1021/am504110u.
[45] T. Chen, M. Zhao, Q. Shi, Z. Yang, H. Liu, L. Sun, J. Ouyang, C. Lee, Novel augmented reality interface using a self-powered triboelectric based virtual reality 3D-control sensor, Nano Energy 51 (2018) 162–172, http://dx.doi.org/10.1016/j.nanoen.2018.06.022.
[46] T. Chen, Q. Shi, M. Zhu, T. He, Z. Yang, H. Liu, L. Sun, L. Yang, C. Lee, Intuitive-augmented human-machine multidimensional nano-manipulation terminal using triboelectric stretchable strip sensors based on minimalist design, Nano Energy 60 (2019) 440–448, http://dx.doi.org/10.1016/j.nanoen.2019.03.071.
[47] Q. Shi, C. Lee, Self-powered bio-inspired spider-net-coding interface using single-electrode triboelectric nanogenerator, Adv. Sci. 1900617 (2019) 1900617, http://dx.doi.org/10.1002/advs.201900617.
[48] Q. Shi, Z. Zhang, T. Chen, C. Lee, Minimalist and multi-functional human machine interface (HMI) using a flexible wearable triboelectric patch, Nano Energy 62 (2019) 355–366, http://dx.doi.org/10.1016/j.nanoen.2019.05.033.
[49] C. Hou, T. Chen, Y. Li, M. Huang, Q. Shi, H. Liu, L. Sun, C. Lee, A rotational pendulum based electromagnetic/triboelectric hybrid-generator for ultra-low-frequency vibrations aiming at human motion and blue energy applications, Nano Energy 63 (2019) 103871, http://dx.doi.org/10.1016/j.nanoen.2019.103871.
[50] W. Kim, D. Bhatia, S. Jeong, D. Choi, Mechanical energy conversion systems for triboelectric nanogenerators: kinematic and vibrational designs, Nano Energy 56 (2018) 307–321, http://dx.doi.org/10.1016/J.NANOEN.2018.11.056.
[51] Q. He, Y. Wu, Z. Feng, C. Sun, W. Fan, Z. Zhou, K. Meng, E. Fan, J. Yang, Triboelectric vibration sensor for a human-machine interface built on ubiquitous surfaces, Nano Energy 59 (2019) 689–696, http://dx.doi.org/10.1016/j.nanoen.2019.03.005.
[52] K.H. Koh, Q. Shi, S. Cao, D. Ma, H.Y. Tan, Z. Guo, C. Lee, A self-powered 3D activity inertial sensor using hybrid sensing mechanisms, Nano Energy 56 (2019) 651–661, http://dx.doi.org/10.1016/j.nanoen.2018.11.075.
[53] Q. Shi, T. He, C. Lee, More than energy harvesting – combining triboelectric nanogenerator and flexible electronics technology for enabling novel micro-/nano-systems, Nano Energy 57 (2019) 851–871, http://dx.doi.org/10.1016/j.nanoen.2019.01.002.
[54] L. Chen, Q. Shi, Y. Sun, T. Nguyen, C. Lee, S. Soh, Controlling surface charge generated by contact electrification: strategies and applications, Adv. Mater. 30 (2018) 1802405, http://dx.doi.org/10.1002/adma.201802405.
[55] X. Wen, Y. Su, Y. Yang, H. Zhang, Z.L. Wang, Applicability of triboelectric generator over a wide range of temperature, Nano Energy 4 (2014) 150–156, http://dx.doi.org/10.1016/j.nanoen.2014.01.001.
[56] R.K. Gupta, Q. Shi, L. Dhakar, T. Wang, C.H. Heng, C. Lee, Broadband energy harvester using non-linear polymer spring and electromagnetic/triboelectric hybrid mechanism, Sci. Rep. 7 (2017) 1–13, http://dx.doi.org/10.1038/srep41396.
[57] L. Pan, J. Wang, P. Wang, R. Gao, Y.-C. Wang, X. Zhang, J.-J. Zou, Z.L. Wang, Liquid-FEP-based U-tube triboelectric nanogenerator for harvesting water-wave energy, Nano Res. (2018) 1–12, http://dx.doi.org/10.1007/s12274-018-1989-9.
[58] B. Zhang, Y. Tang, R. Dai, H. Wang, X. Sun, C. Qin, Z. Pan, E. Liang, Y. Mao, Breath-based human–machine interaction system using triboelectric nanogenerator, Nano Energy 64 (2019) 103953, http://dx.doi.org/10.1016/j.nanoen.2019.103953.
[59] T. He, H. Wang, J. Wang, X. Tian, F. Wen, Q. Shi, J.S. Ho, C. Lee, Self-sustainable wearable textile nano-energy nano-system (NENS) for next-generation healthcare applications, Adv. Sci. 6 (2019) 1901437, http://dx.doi.org/10.1002/advs.201901437.
[60] Y.C. Lai, J. Deng, S.L. Zhang, S. Niu, H. Guo, Z.L. Wang, Single-thread-based wearable and highly stretchable triboelectric nanogenerators and their applications in cloth-based self-powered human-interactive and biomedical sensing, Adv. Funct. Mater. 27 (2017), http://dx.doi.org/10.1002/adfm.201604462.
[61] T. Chen, Q. Shi, M. Zhu, T. He, L. Sun, L. Yang, C. Lee, Triboelectric self-powered wearable flexible patch as 3D motion control interface for robotic manipulator, ACS Nano 12 (2018) 11561–11571, http://dx.doi.org/10.1021/acsnano.8b06747.
[62] H. Wang, H. Wu, D. Hasan, T. He, Q. Shi, C. Lee, Self-powered dual-mode amenity sensor based on the water-air triboelectric nanogenerator, ACS Nano 11 (2017) 10337–10346, http://dx.doi.org/10.1021/acsnano.7b05213.
[63] M. Matsunaga, J. Hirotani, S. Kishimoto, Y. Ohno, High-output, transparent, stretchable triboelectric nanogenerator based on carbon nanotube thin film toward wearable energy harvesters, Nano Energy 67 (2020) 104297, http://dx.doi.org/10.1016/j.nanoen.2019.104297.
[64] D. Liu, X. Yin, H. Guo, L. Zhou, X. Li, C. Zhang, J. Wang, Z.L. Wang, A constant current triboelectric nanogenerator arising from electrostatic breakdown, Sci. Adv. 5 (2019), http://dx.doi.org/10.1126/sciadv.aav6437.
[65] H. Wang, Z. Xiang, P. Giorgia, X. Mu, Y. Yang, Z.L. Wang, C. Lee, Triboelectric liquid volume sensor for self-powered lab-on-chip applications, Nano Energy 23 (2016) 80–88, http://dx.doi.org/10.1016/j.nanoen.2016.02.054.
[66] Q. Shi, H. Wu, H. Wang, H. Wu, C. Lee, Self-powered gyroscope ball using a triboelectric mechanism, Adv. Energy Mater. 7 (2017) 1–11, http://dx.doi.org/10.1002/aenm.201701300.
[67] Y. Wu, Y. Hu, Z. Huang, C. Lee, F. Wang, Electret-material enhanced triboelectric energy harvesting from air flow for self-powered wireless temperature sensor network, Sensors Actuators, A Phys. 271 (2018) 364–372, http://dx.doi.org/10.1016/j.sna.2017.12.067.
[68] Y. Lee, J. Kim, B. Jang, S. Kim, B.K. Sharma, J.H. Kim, J.H. Ahn, Graphene-based stretchable/wearable self-powered touch sensor, Nano Energy 62 (2019) 259–267, http://dx.doi.org/10.1016/j.nanoen.2019.05.039.
[69] L. Dhakar, P. Pitchappa, F.E.H. Tay, C. Lee, An intelligent skin based self-powered finger motion sensor integrated with triboelectric nanogenerator, Nano Energy 19 (2016) 532–540, http://dx.doi.org/10.1016/j.nanoen.2015.04.020.
[70] T. Chen, Q. Shi, K. Li, Z. Yang, H. Liu, L. Sun, J.A. Dziuban, C. Lee, Investigation of position sensing and energy harvesting of a flexible triboelectric touch pad, Nanomaterials 8 (2018) 1–15, http://dx.doi.org/10.3390/nano8080613.
[71] Q. Shi, H. Wang, T. Wang, C. Lee, Self-powered liquid triboelectric microfluidic sensor for pressure sensing and finger motion monitoring applications, Nano Energy 30 (2016) 450–459, http://dx.doi.org/10.1016/j.nanoen.2016.10.046.
[72] M.A. Halim, H.O. Cho, J.Y. Park, A handy motion driven, frequency up-converting piezoelectric energy harvester using flexible base for wearable sensors applications, in: 2015 IEEE SENSORS, IEEE, 2015, pp. 1–4, http://dx.doi.org/10.1109/ICSENS.2015.7370437.
[73] M.A. Halim, J.Y. Park, Piezoelectric energy harvester using impact-driven flexible side-walls for human-limb motion, Microsyst. Technol. 24 (2018) 2099–2107, http://dx.doi.org/10.1007/s00542-016-3268-6.
[74] S. Khalifa, G. Lan, M. Hassan, A. Seneviratne, S.K. Das, HARKE: human activity recognition from kinetic energy harvesting data in wearable devices, IEEE Trans. Mob. Comput. 17 (2018) 1353–1368, http://dx.doi.org/10.1109/TMC.2017.2761744.
[75] P. Pillatsch, P.K. Wright, E.M. Yeatman, A.S. Holmes, A wireless charging mechanism for a rotational human motion energy harvester, in: 2015 IEEE 12th Int. Conf. Wearable Implant. Body Sens. Networks, IEEE, 2015, pp. 1–5, http://dx.doi.org/10.1109/BSN.2015.7299395.
[76] T. Xue, X. Ma, C. Rahn, S. Roundy, Analysis of upper bound power output for a wrist-worn rotational energy harvester from real-world measured inputs, J. Phys. Conf. Ser. 557 (2014) 012090, http://dx.doi.org/10.1088/1742-6596/557/1/012090.
[77] Y. Bai, P. Tofel, Z. Hadas, J. Smilek, P. Losak, P. Skarvada, R. Macku, Investigation of a cantilever structured piezoelectric energy harvester used for wearable devices with random vibration input, Mech. Syst. Signal Process. 106 (2018) 303–318, http://dx.doi.org/10.1016/j.ymssp.2018.01.006.
[78] T. Xue, H.G. Yeo, S. Trolier-McKinstry, S. Roundy, Wearable inertial energy harvester with sputtered bimorph lead zirconate titanate (PZT) thin-film beams, Smart Mater. Struct. 27 (2018) 085026, http://dx.doi.org/10.1088/1361-665X/aad037.
[79] J. Manjarres, K. Dasuki, H. Parody, O. Gomez, M. Pardo, Monitoring system for kinetic energy harvesting in a Mobile platform, in: 2019 IEEE Int. Symp. Circuits Syst., IEEE, 2019, pp. 1–5, http://dx.doi.org/10.1109/ISCAS.2019.8702657.
[80] A. Proto, B. Fida, I. Bernabucci, D. Bibbo, S. Conforto, M. Schmid, K. Vlach, V. Kasik, M. Penhaker, Wearable PVDF transducer for biomechanical energy harvesting and gait cycle detection, in: 2016 IEEE EMBS Conf. Biomed. Eng. Sci., IEEE, 2016, pp. 62–66, http://dx.doi.org/10.1109/IECBES.2016.7843415.
[81] B. Yang, K.-S. Yun, Piezoelectric shell structures as wearable energy harvesters for effective power generation at low-frequency movement,

Sensors Actuators A Phys. 188 (2012) 427–433, http://dx.doi.org/10.1016/j.sna.2012.03.026.
[82] S.S. Won, M. Sheldon, N. Mostovych, J. Kwak, B.-S. Chang, C.W. Ahn, A.I. Kingon, I.W. Kim, S.-H. Kim, Piezoelectric poly(vinylidene fluoride trifluoroethylene) thin film-based power generators using paper substrates for wearable device applications, Appl. Phys. Lett. 107 (2015) 202901, http://dx.doi.org/10.1063/1.4935557.
[83] M. Pozzi, M. Zhu, Plucked piezoelectric bimorphs for knee-joint energy harvesting: modelling and experimental validation, Smart Mater. Struct. 20 (2011) 055007, http://dx.doi.org/10.1088/0964-1726/20/5/055007.
[84] M. Pozzi, M.S.H. Aung, M. Zhu, R.K. Jones, J.Y. Goulermas, The pizzicato knee-joint energy harvester: characterization with biomechanical data and the effect of backpack load, Smart Mater. Struct. 21 (2012) 075023, http://dx.doi.org/10.1088/0964-1726/21/7/075023.
[85] M. Pozzi, M. Zhu, Characterization of a rotary piezoelectric energy harvester based on plucking excitation for knee-joint wearable applications, Smart Mater. Struct. 21 (2012) 055004, http://dx.doi.org/10.1088/0964-1726/21/5/055004.
[86] M. Pozzi, Magnetic plucking of piezoelectric bimorphs for a wearable energy harvester, Smart Mater. Struct. 25 (2016) 045008, http://dx.doi.org/10.1088/0964-1726/25/4/045008.
[87] Y. Kuang, M. Zhu, Characterisation of a knee-joint energy harvester powering a wireless communication sensing node, Smart Mater. Struct. 25 (2016) 055013, http://dx.doi.org/10.1088/0964-1726/25/5/055013.
[88] Y. Kuang, T. Ruan, Z.J. Chew, M. Zhu, Energy harvesting during human walking to power a wireless sensor node, Sensors Actuators A Phys. 254 (2017) 69–77, http://dx.doi.org/10.1016/j.sna.2016.11.035.
[89] J. Zhao, Z. You, A shoe-embedded piezoelectric energy harvester for wearable sensors, Sensors 14 (2014) 12497–12510, https://doi.org/10.3390/s140712497.
[90] H. Kalantarian, M. Sarrafzadeh, Pedometers without batteries: an energy harvesting shoe, IEEE Sens. J. 16 (2016) 1, http://dx.doi.org/10.1109/JSEN.2016.2591331.
[91] R. Hua, H. Liu, H. Yang, Y. Wang, J. Ferrante, A nonlinear interface integrated lever mechanism for piezoelectric footstep energy harvesting, Appl. Phys. Lett. 113 (2018), 053902, http://dx.doi.org/10.1063/1.5041259.
[92] F. Qian, T.-B. Xu, L. Zuo, Design, optimization, modeling and testing of a piezoelectric footwear energy harvester, Energy Convers. Manage. 171 (2018) 1352–1364, http://dx.doi.org/10.1016/j.enconman.2018.06.069.
[93] S. Singh, V.K. Gupta, S. Mukherjee, Piezoelectric based energy harvesterembedded in shoe forwearable electronics, Mater. Phys. Mech. 37 (2018) 159–167, http://dx.doi.org/10.18720/MPM.3722018-8.
[94] F. Chen, M. He, S. Wang, X. Zhong, M. Guan, Study of an inertial piezoelectric energy harvester from a backpack, Ferroelectrics 550 (2019) 233–243, http://dx.doi.org/10.1080/00150193.2019.1652513.
[95] M.B. Khan, D.H. Kim, J.H. Han, H. Saif, H. Lee, Y. Lee, M. Kim, E. Jang, S.K. Hong, D.J. Joe, T.-I. Lee, T.-S. Kim, K.J. Lee, Y. Lee, Performance improvement of flexible piezoelectric energy harvester for irregular human motion with energy extraction enhancement circuit, Nano Energy 58 (2019) 211–219, http://dx.doi.org/10.1016/j.nanoen.2019.01.049.
[96] K. Li, Q. He, J. Wang, Z. Zhou, X. Li, Wearable energy harvesters generating electricity from low-frequency human limb movement, Microsystems Nanoeng. 4 (2018) 24, http://dx.doi.org/10.1038/s41378-018-0024-3.
[97] R. Lockhart, P. Janphuang, D. Briand, N.F. de Rooij, A wearable system of micromachined piezoelectric cantilevers coupled to a rotational oscillating mass for on-body energy harvesting, in: 2014 IEEE 27th Int. Conf. Micro Electro Mech. Syst., IEEE, 2014, pp. 370–373, http://dx.doi.org/10.1109/MEMSYS.2014.6765653.
[98] M. Han, H. Wang, Y. Yang, C. Liang, W. Bai, Z. Yan, H. Li, Y. Xue, X. Wang, B. Akar, H. Zhao, H. Luan, J. Lim, I. Kandela, G.A. Ameer, Y. Zhang, Y. Huang, J.A. Rogers, Three-dimensional piezoelectric polymer microsystems for vibrational energy harvesting, robotic interfaces and biomedical implants, Nat. Electron. 2 (2019) 26–35, http://dx.doi.org/10.1038/s41928-018-0189-7.
[99] H.G. Yeo, T. Xue, S. Roundy, X. Ma, C. Rahn, S. Trolier-McKinstry, Strongly (001) oriented bimorph PZT film on metal foils grown by rf -sputtering for wrist-worn piezoelectric energy harvesters, Adv. Funct. Mater. 28 (2018) 1801327, http://dx.doi.org/10.1002/adfm.201801327.
[100] X. Wang, W.-Z. Song, M.-H. You, J. Zhang, M. Yu, Z. Fan, S. Ramakrishna, Y.-Z. Long, Bionic single-electrode electronic skin unit based on piezoelectric nanogenerator, ACS Nano 12 (2018) 8588–8596, http://dx.doi.org/10.1021/acsnano.8b04244.
[101] J.-H. Lee, K.Y. Lee, B. Kumar, N.T. Tien, N.-E. Lee, S.-W. Kim, Highly sensitive stretchable transparent piezoelectric nanogenerators, Energy Environ. Sci. 6 (2013) 169–175, http://dx.doi.org/10.1039/C2EE23530G.
[102] S.K. Karan, S. Maiti, S. Paria, A. Maitra, S.K. Si, J.K. Kim, B.B. Khatua, A new insight towards eggshell membrane as high energy conversion efficient bio-piezoelectric energy harvester, Mater. Today Energy. 9 (2018) 114–125, http://dx.doi.org/10.1016/j.mtener.2018.05.006.
[103] M. Lee, C.-Y. Chen, S. Wang, S.N. Cha, Y.J. Park, J.M. Kim, L.-J. Chou, Z.L. Wang, A hybrid piezoelectric structure for wearable nanogenerators, Adv. Mater. 24 (2012) 1759–1764, http://dx.doi.org/10.1002/adma.201200150.
[104] W. Wu, S. Bai, M. Yuan, Y. Qin, Z.L. Wang, T. Jing, Lead zirconate titanate nanowire textile nanogenerator for wearable energy-harvesting and self-powered devices, ACS Nano 6 (2012) 6231–6235, http://dx.doi.org/10.1021/nn3016585.
[105] L. Lu, B. Yang, Y. Zhai, J. Liu, Electrospinning core-sheath piezoelectric microfibers for self-powered stitchable sensor, Nano Energy 76 (2020) 104966, http://dx.doi.org/10.1016/j.nanoen.2020.104966.
[106] S. Bai, L. Zhang, Q. Xu, Y. Zheng, Y. Qin, Z.L. Wang, Two dimensional woven nanogenerator, Nano Energy 2 (2013) 749–753, http://dx.doi.org/10.1016/j.nanoen.2013.01.001.
[107] W. Zeng, X.-M. Tao, S. Chen, S. Shang, H.L.W. Chan, S.H. Choy, Highly durable all-fiber nanogenerator for mechanical energy harvesting, Energy Environ. Sci. 6 (2013) 2631, http://dx.doi.org/10.1039/c3ee41063c.
[108] S. Song, K.-S. Yun, Design and characterization of scalable woven piezoelectric energy harvester for wearable applications, Smart Mater. Struct. 24 (2015) 045008, http://dx.doi.org/10.1088/0964-1726/24/4/045008.
[109] H. Jun Sim, C. Choi, C. Jun Lee, Y. Tae Kim, S. Jeong Kim, Flexible two-ply piezoelectric yarn energy harvester, Curr. Nanosci. 11 (2015) 539–544, http://dx.doi.org/10.2174/1573413711666150225231434.
[110] M. Zhang, T. Gao, J. Wang, J. Liao, Y. Qiu, Q. Yang, H. Xue, Z. Shi, Y. Zhao, Z. Xiong, L. Chen, A hybrid fibers based wearable fabric piezoelectric nanogenerator for energy harvesting application, Nano Energy 13 (2015) 298–305, http://dx.doi.org/10.1016/j.nanoen.2015.02.034.
[111] H. Gao, P.T. Minh, H. Wang, S. Minko, J. Locklin, T. Nguyen, S. Sharma, High-performance flexible yarn for wearable piezoelectric nanogenerators, Smart Mater. Struct. 27 (2018) 095018, http://dx.doi.org/10.1088/1361-665X/aad718.
[112] H. Gao, D. Asheghali, N.S. Yadavalli, M.T. Pham, T.D. Nguyen, S. Minko, S. Sharma, Fabrication of core-sheath nanoyarn via touchspinning and its application in wearable piezoelectric nanogenerator, J. Text. Inst. 111 (2020) 906–915, http://dx.doi.org/10.1080/00405000.2019.1678558.
[113] Q. Zhang, Z. Zhang, Q. Liang, F. Gao, F. Yi, M. Ma, Q. Liao, Z. Kang, Y. Zhang, Green hybrid power system based on triboelectric nanogenerator for wearable/portable electronics, Nano Energy 55 (2019) 151–163, http://dx.doi.org/10.1016/j.nanoen.2018.10.078.
[114] W. Ding, A.C. Wang, C. Wu, H. Guo, Z.L. Wang, Human–machine interfacing enabled by triboelectric nanogenerators and tribotronics, Adv. Mater. Technol. 4 (2019) 1–16, http://dx.doi.org/10.1002/admt.201800487.
[115] B. Chen, Y. Yang, Z.L. Wang, Scavenging wind energy by triboelectric nanogenerators, Adv. Energy Mater. 8 (2018) 1–13, http://dx.doi.org/10.1002/aenm.201702649.
[116] K. Dong, X. Peng, Z.L. Wang, Fiber/fabric-based piezoelectric and triboelectric nanogenerators for flexible/stretchable and wearable electronics and artificial intelligence, Adv. Mater. 32 (2020) 1902549, http://dx.doi.org/10.1002/adma.201902549.
[117] K. Dong, Y.C. Wang, J. Deng, Y. Dai, S.L. Zhang, H. Zou, B. Gu, B. Sun, Z.L. Wang, A highly stretchable and washable all-yarn-based self-charging knitting power textile composed of fiber triboelectric nanogenerators and supercapacitors, ACS Nano 11 (2017) 9490–9499, http://dx.doi.org/10.1021/acsnano.7b05317.
[118] X. Pu, L. Li, H. Song, C. Du, Z. Zhao, C. Jiang, G. Cao, W. Hu, Z.L. Wang, A self-charging power unit by integration of a textile triboelectric nanogenerator and a flexible lithium-ion battery for wearable electronics, Adv. Mater. 27 (2015) 2472–2478, http://dx.doi.org/10.1002/adma.201500311.
[119] S.S. Kwak, H.J. Yoon, S.W. Kim, Textile-based triboelectric nanogenerators for self-powered wearable electronics, Adv. Funct. Mater. 29 (2019) 1–26, http://dx.doi.org/10.1002/adfm.201804533.
[120] L. Liu, J. Pan, P. Chen, J. Zhang, X. Yu, X. Ding, B. Wang, X. Sun, H. Peng, A triboelectric textile templated by a three-dimensionally penetrated fabric, J. Mater. Chem. A 4 (2016) 6077–6083, http://dx.doi.org/10.1039/c6ta01166g.
[121] M. Zhu, Y. Huang, W.S. Ng, J. Liu, Z. Wang, Z. Wang, H. Hu, C. Zhi, 3D spacer fabric based multifunctional triboelectric nanogenerator with great feasibility for mechanized large-scale production, Nano Energy 27 (2016) 439–446, http://dx.doi.org/10.1016/j.nanoen.2016.07.016.
[122] B. Dudem, A.R. Mule, H.R. Patnam, J.S. Yu, Wearable and durable triboelectric nanogenerators via polyaniline coated cotton textiles as a movement sensor and self-powered system, Nano Energy 55 (2019) 305–315, http://dx.doi.org/10.1016/j.nanoen.2018.10.074.
[123] R. Cao, X. Pu, X. Du, W. Yang, J. Wang, H. Guo, S. Zhao, Z. Yuan, C. Zhang, C. Li, Z.L. Wang, Screen-printed washable electronic textiles as self-powered Touch/Gesture tribo-sensors for intelligent human-machine interaction, ACS Nano 12 (2018) 5190–5196, http://dx.doi.org/10.1021/acsnano.8b02477.
[124] J. Xiong, M.F. Lin, J. Wang, S.L. Gaw, K. Parida, P.S. Lee, Wearable all-fabric-Based triboelectric generator for water energy harvesting, Adv. Energy Mater. 7 (2017) 1–10, http://dx.doi.org/10.1002/aenm.201701243.
[125] G. Chen, Y. Li, M. Bick, J. Chen, Smart textiles for electricity generation, Chem. Rev. 120 (2020) 3668–3720, http://dx.doi.org/10.1021/acs.chemrev.9b00821.
[126] J. Shi, S. Liu, L. Zhang, B. Yang, L. Shu, Y. Yang, M. Ren, Y. Wang, J. Chen, W. Chen, Y. Chai, X. Tao, Smart textile-integrated microelectronic systems for wearable applications, Adv. Mater. 1901958 (2019) 1–37, http://dx.doi.org/10.1002/adma.201901958.
[127] W. Paosangthong, R. Torah, S. Beeby, Recent progress on textile-based triboelectric nanogenerators, Nano Energy 55 (2019) 401–423, http://dx.doi.org/10.1016/j.nanoen.2018.10.036.
[128] J. Xiong, P. Cui, X. Chen, J. Wang, K. Parida, M.-F. Lin, P.S. Lee, Skin-touch-actuated textile-based triboelectric nanogenerator with black

phosphorus for durable biomechanical energy harvesting, Nat. Commun. 9 (2018) 4280, http://dx.doi.org/10.1038/s41467-018-06759-0.
[129] L. Zhang, Y. Yu, G.P. Eyer, G. Suo, L.A. Kozik, M. Fairbanks, X. Wang, T.L. Andrew, All-textile triboelectric generator compatible with traditional textile process, Adv. Mater. Technol. 1 (2016) 1600147, http://dx.doi.org/10.1002/admt.201600147.
[130] T. Huang, J. Zhang, B. Yu, H. Yu, H. Long, H. Wang, Q. Zhang, M. Zhu, Fabric texture design for boosting the performance of a knitted washable textile triboelectric nanogenerator as wearable power, Nano Energy 58 (2019) 375–383, http://dx.doi.org/10.1016/j.nanoen.2019.01.038.
[131] W. Wang, A. Yu, X. Liu, Y. Liu, Y. Zhang, Y. Zhu, Y. Lei, M. Jia, J. Zhai, Z.L. Wang, Large-scale fabrication of robust textile triboelectric nanogenerators, Nano Energy 71 (2020) 104605, http://dx.doi.org/10.1016/j.nanoen.2020.104605.
[132] J. Chen, Y. Huang, N. Zhang, H. Zou, R. Liu, C. Tao, X. Fan, Z.L. Wang, Micro-cable structured textile for simultaneously harvesting solar and mechanical energy, Nat. Energy. 1 (2016) 1–8, http://dx.doi.org/10.1038/nenergy.2016.138.
[133] X. Pu, L. Li, M. Liu, C. Jiang, C. Du, Z. Zhao, W. Hu, Z.L. Wang, Wearable self-charging power textile based on flexible yarn supercapacitors and fabric nanogenerators, Adv. Mater. 28 (2016) 98–105, http://dx.doi.org/10.1002/adma.201504403.
[134] Z. Cong, W. Guo, Z. Guo, Y. Chen, M. Liu, T. Hou, X. Pu, W. Hu, Z.L. Wang, Stretchable coplanar self-charging power textile with resist-dyeing triboelectric nanogenerators and microsupercapacitors, ACS Nano 14 (2020) 5590–5599, http://dx.doi.org/10.1021/acsnano.9b09994.
[135] S.S. Kwak, H. Kim, W. Seung, J. Kim, R. Hinchet, S.-W. Kim, Fully stretchable textile triboelectric nanogenerator with knitted fabric structures, ACS Nano 11 (2017) 10733–10741, http://dx.doi.org/10.1021/acsnano.7b05203.
[136] Q. Jiang, C. Wu, Z. Wang, A.C. Wang, J.H. He, Z.L. Wang, H.N. Alshareef, MXene electrochemical microsupercapacitor integrated with triboelectric nanogenerator as a wearable self-charging power unit, Nano Energy 45 (2018) 266–272, http://dx.doi.org/10.1016/j.nanoen.2018.01.004.
[137] M. Zhu, Q. Shi, T. He, Z. Yi, Y. Ma, B. Yang, T. Chen, C. Lee, Self-powered and self-functional cotton sock using piezoelectric and triboelectric hybrid mechanism for healthcare and sports monitoring, ACS Nano 13 (2019), http://dx.doi.org/10.1021/acsnano.8b08329, acsnano.8b08329.
[138] G. Zhu, P. Bai, J. Chen, Z. Lin Wang, Power-generating shoe insole based on triboelectric nanogenerators for self-powered consumer electronics, Nano Energy 2 (2013) 688–692, http://dx.doi.org/10.1016/j.nanoen.2013.08.002.
[139] S. Li, J. Wang, W. Peng, L. Lin, Y. Zi, S. Wang, G. Zhang, Z.L. Wang, Sustainable energy source for wearable electronics based on multilayer elastomeric triboelectric nanogenerators, Adv. Energy Mater. 7 (2017), http://dx.doi.org/10.1002/aenm.201602832.
[140] J. Qi, A.C. Wang, W. Yang, M. Zhang, C. Hou, Q. Zhang, Y. Li, H. Wang, Hydrogel-based hierarchically wrinkled stretchable nanofibrous membrane for high performance wearable triboelectric nanogenerator, Nano Energy 67 (2020) 104206, http://dx.doi.org/10.1016/j.nanoen.2019.104206.
[141] Z. Wen, Y. Yang, N. Sun, G. Li, Y. Liu, C. Chen, J. Shi, L. Xie, H. Jiang, D. Bao, Q. Zhuo, X. Sun, A wrinkled PEDOT:PSS film based stretchable and transparent triboelectric nanogenerator for wearable energy harvesters and active motion sensors, Adv. Funct. Mater. 28 (2018) 1803684, http://dx.doi.org/10.1002/adfm.201803684.
[142] J. Sun, X. Pu, M. Liu, A. Yu, C. Du, J. Zhai, W. Hu, Z.L. Wang, Self-healable, stretchable, transparent triboelectric nanogenerators as soft power sources, ACS Nano 12 (2018) 6147–6155, http://dx.doi.org/10.1021/acsnano.8b02479.
[143] Z. Qin, Y. Yin, W. Zhang, C. Li, K. Pan, Wearable and stretchable triboelectric nanogenerator based on crumpled nanofibrous membranes, ACS Appl. Mater. Interfaces 11 (2019) 12452–12459, http://dx.doi.org/10.1021/acsami.8b21487.
[144] C. Du, W. Hu, X. Pu, Y. Zhang, J. Sun, M. Liu, J. Zhai, Z.L. Wang, X. Chen, Ultrastretchable, transparent triboelectric nanogenerator as electronic skin for biomechanical energy harvesting and tactile sensing, Sci. Adv. 3 (2017) e1700015, http://dx.doi.org/10.1126/sciadv.1700015.
[145] L. Zhang, C. Su, L. Cheng, N. Cui, L. Gu, Y. Qin, R. Yang, F. Zhou, Enhancing the performance of textile triboelectric nanogenerators with oblique microrod arrays for wearable energy harvesting, ACS Appl. Mater. Interfaces 11 (2019) 26824–26829, http://dx.doi.org/10.1021/acsami.9b06627.
[146] W. Jiang, H. Li, Z. Liu, Z. Li, J. Tian, B. Shi, Y. Zou, H. Ouyang, C. Zhao, L. Zhao, R. Sun, H. Zheng, Y. Fan, Z.L. Wang, Z. Li, Fully bioabsorbable natural-materials-based triboelectric nanogenerators, Adv. Mater. 30 (2018) 1–10, http://dx.doi.org/10.1002/adma.201801895.
[147] Y. Han, Y. Han, X. Zhang, L. Li, C. Zhang, J. Liu, G. Lu, H.-D. Yu, W. Huang, Fish gelatin based triboelectric nanogenerator for harvesting biomechanical energy and self-powered sensing of human physiological signals, ACS Appl. Mater. Interfaces (2020), http://dx.doi.org/10.1021/acsami.0c01061.
[148] Z. Liu, Z. Zhao, X. Zeng, X. Fu, Y. Hu, Nano Energy Expandable microsphere-based triboelectric nanogenerators as ultrasensitive pressure sensors for respiratory and pulse monitoring, Nano Energy 59 (2019) 295–301, http://dx.doi.org/10.1016/j.nanoen.2019.02.057.
[149] T. Bu, T. Xiao, Z. Yang, G. Liu, X. Fu, J. Nie, T. Guo, Y. Pang, J. Zhao, F. Xi, C. Zhang, Z.L. Wang, Stretchable triboelectric-photonic smart skin for tactile and gesture sensing, Adv. Mater. 30 (2018) 1800066, http://dx.doi.org/10.1002/adma.201800066.
[150] S. Chun, C. Pang, S.B. Cho, A micropillar-assisted versatile strategy for highly sensitive and efficient triboelectric energy generation under in-plane stimuli, Adv. Mater. 32 (2020) 1–8, http://dx.doi.org/10.1002/adma.201905539.
[151] G. Liu, S. Xu, Y. Liu, Y. Gao, T. Tong, Y. Qi, C. Zhang, Flexible drug release device powered by triboelectric nanogenerator, Adv. Funct. Mater. 1909886 (2020) 1–9, http://dx.doi.org/10.1002/adfm.201909886.
[152] T. Quan, X. Wang, Z.L. Wang, Y. Yang, Hybridized Electromagnetic-Triboelectric Nanogenerator for a self-powered electronic watch, ACS Nano 9 (2015) 12301–12310, http://dx.doi.org/10.1021/acsnano.5b05598.
[153] X. Chen, H. Guo, H. Wu, H. Chen, Y. Song, Z. Su, Nano Energy Hybrid generator based on freestanding magnet as all-direction in-plane energy harvester and vibration sensor, Nano Energy 49 (2018) 51–58, http://dx.doi.org/10.1016/j.nanoen.2018.04.024.
[154] C. Rodrigues, A. Gomes, A. Ghosh, A. Pereira, J. Ventura, Power-generating footwear based on a triboelectric-electromagnetic-piezoelectric hybrid nanogenerator, Nano Energy 62 (2019) 660–666, http://dx.doi.org/10.1016/j.nanoen.2019.05.063.
[155] S. Gong, B. Zhang, J. Zhang, Z.L. Wang, K. Ren, Biocompatible poly(lactic acid)-based hybrid piezoelectric and Electret Nanogenerator for electronic skin applications, Adv. Funct. Mater. 30 (2020) 1908724, http://dx.doi.org/10.1002/adfm.201908724.
[156] C. Dagdeviren, B.D. Yang, Y. Su, P.L. Tran, P. Joe, E. Anderson, J. Xia, V. Doraiswamy, B. Dehdashti, X. Feng, B. Lu, R. Poston, Z. Khalpey, R. Ghaffari, Y. Huang, M.J. Slepian, J.A. Rogers, Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm, Proc. Natl. Acad. Sci. 111 (2014) 1927–1932, http://dx.doi.org/10.1073/pnas.1317233111.
[157] W. Li, X. Xu, C. Liu, M.C. Tekell, J. Ning, J. Guo, J. Zhang, D. Fan, Ultralight and binder-free all-solid-state flexible supercapacitors for powering wearable strain sensors, Adv. Funct. Mater. 27 (2017) 1702738, http://dx.doi.org/10.1002/adfm.201702738.
[158] D.H. Kim, H.J. Shin, H. Lee, C.K. Jeong, H. Park, G.-T. Hwang, H.-Y. Lee, D.J. Joe, J.H. Han, S.H. Lee, J. Kim, B. Joung, K.J. Lee, In vivo self-powered wireless transmission using biocompatible flexible energy harvesters, Adv. Funct. Mater. 27 (2017) 1700341, http://dx.doi.org/10.1002/adfm.201700341.
[159] L. Halámková, J. Halámek, V. Bocharova, A. Szczupak, L. Alfonta, E. Katz, Implanted biofuel cell operating in a living snail, J. Am. Chem. Soc. 134 (2012) 5040–5043, http://dx.doi.org/10.1021/ja211714w.
[160] P.P. Mercier, A.C. Lysaght, S. Bandyopadhyay, A.P. Chandrakasan, K.M. Stankovic, Energy extraction from the biologic battery in the inner ear, Nat. Biotechnol. 30 (2012) 1240–1243, http://dx.doi.org/10.1038/nbt.2394.
[161] G.-T. Hwang, H. Park, J.-H. Lee, S. Oh, K.-I. Park, M. Byun, H. Park, G. Ahn, C.K. Jeong, K. No, H. Kwon, S.-G. Lee, B. Joung, K.J. Lee, Self-powered cardiac pacemaker enabled by flexible single crystalline PMN-PT piezoelectric energy harvester, Adv. Mater. 26 (2014) 4880–4887, http://dx.doi.org/10.1002/adma.201400562.
[162] Q. Zheng, B. Shi, F. Fan, X. Wang, L. Yan, W. Yuan, S. Wang, H. Liu, Z. Li, Z.L. Wang, In vivo powering of pacemaker by breathing-driven implanted triboelectric nanogenerator, Adv. Mater. 26 (2014) 5851–5856, http://dx.doi.org/10.1002/adma.201402064.
[163] Q. Zheng, H. Zhang, B. Shi, X. Xue, Z. Liu, Y. Jin, Y. Ma, Y. Zou, X. Wang, Z. An, W. Tang, W. Zhang, F. Yang, Y. Liu, X. Lang, Z. Xu, Z. Li, Z.L. Wang, In vivo self-powered wireless cardiac monitoring via implantable triboelectric nanogenerator, ACS Nano 10 (2016) 6510–6518, http://dx.doi.org/10.1021/acsnano.6b02693.
[164] Y. Ma, Q. Zheng, Y. Liu, B. Shi, X. Xue, W. Ji, Z. Liu, Y. Jin, Y. Zou, Z. An, W. Zhang, X. Wang, W. Jiang, Z. Xu, Z.L. Wang, Z. Li, H. Zhang, Self-powered, one-stop, and multifunctional implantable triboelectric active sensor for real-time biomedical monitoring, Nano Lett. 16 (2016) 6042–6051, http://dx.doi.org/10.1021/acs.nanolett.6b01968.
[165] K. Song, J.H. Han, T. Lim, N. Kim, S. Shin, J. Kim, H. Choo, S. Jeong, Y.-C. Kim, Z.L. Wang, J. Lee, Subdermal flexible solar cell arrays for powering medical electronic implants, Adv. Healthc. Mater. 5 (2016) 1572–1580, http://dx.doi.org/10.1002/adhm.201600222.
[166] X. Cheng, X. Xue, Y. Ma, M. Han, W. Zhang, Z. Xu, H. Zhang, H. Zhang, Implantable and self-powered blood pressure monitoring based on a piezoelectric thinfilm: simulated, in vitro and in vivo studies, Nano Energy 22 (2016) 453–460, http://dx.doi.org/10.1016/j.nanoen.2016.02.037.
[167] C.K. Jeong, K.-I. Park, J.H. Son, G.-T. Hwang, S.H. Lee, D.Y. Park, H.E. Lee, H.K. Lee, M. Byun, K.J. Lee, Self-powered fully-flexible light-emitting system enabled by flexible energy harvester, Energy Environ. Sci. 7 (2014) 4035–4043, http://dx.doi.org/10.1039/C4EE02435D.
[168] G.-T. Hwang, Y. Kim, J.-H. Lee, S. Oh, C.K. Jeong, D.Y. Park, J. Ryu, H. Kwon, S.-G. Lee, B. Joung, D. Kim, K.J. Lee, Self-powered deep brain stimulation via a flexible PIMNT energy harvester, Energy Environ. Sci. 8 (2015) 2677–2684, http://dx.doi.org/10.1039/C5EE01593F.
[169] B.-Y. Kim, W.-H. Lee, H.-G. Hwang, D.-H. Kim, J.-H. Kim, S.-H. Lee, S. Nahm, Resistive switching memory integrated with nanogenerator for self-powered bioimplantable devices, Adv. Funct. Mater. 26 (2016) 5211–5221, http://dx.doi.org/10.1002/adfm.201505569.
[170] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, Z.L. Wang, Self-powered nanowire devices, Nat. Nanotechnol. 5 (2010) 366–373, http://dx.doi.org/10.1038/nnano.2010.46.

[171] B. Shi, Z. Li, Y. Fan, Implantable energy-harvesting devices, Adv. Mater. 1801511 (2018) 1801511, http://dx.doi.org/10.1002/adma.201801511.
[172] S.A. Han, J.H. Lee, W. Seung, J. Lee, S.W. Kim, J.H. Kim, Patchable and implantable 2D nanogenerator, Small 1903519 (2019) 1–14, http://dx.doi.org/10.1002/smll.201903519.
[173] S. Lee, Q. Shi, C. Lee, From flexible electronics technology in the era of IoT and artificial intelligence toward future implanted body sensor networks, APL Mater. 7 (2019), 031302, http://dx.doi.org/10.1063/1.5063498.
[174] B.Z. Li, G. Zhu, R. Yang, A.C. Wang, Z.L. Wang, Muscle-Driven In Vivo Nanogenerator, 2010, pp. 2534–2537, http://dx.doi.org/10.1002/adma.200904355.
[175] A. Zurbuchen, A. Pfenniger, A. Stahel, C.T. Stoeck, S. Vandenberghe, V.M. Koch, R. Vogel, Energy harvesting from the beating heart by a mass imbalance oscillation generator, Ann. Biomed. Eng. 41 (2013) 131–141, http://dx.doi.org/10.1007/s10439-012-0623-3.
[176] C. Sun, J. Shi, D.J. Bayerl, X. Wang, PVDF microbelts for harvesting energy from respiration, Energy Environ. Sci. 4 (2011) 4508, http://dx.doi.org/10.1039/c1ee02241e.
[177] C. Dagdeviren, Y. Shi, P. Joe, R. Ghaffari, G. Balooch, K. Usgaonkar, O. Gur, P.L. Tran, J.R. Crosby, M. Meyer, Y. Su, R. Chad Webb, A.S. Tedesco, M.J. Slepian, Y. Huang, J.A. Rogers, Conformal piezoelectric systems for clinical and experimental characterization of soft tissue biomechanics, Nat. Mater. 14 (2015) 728–736, http://dx.doi.org/10.1038/nmat4289.
[178] M. Madhavan, S.K. Mulpuru, C.J. McLeod, Y.-M. Cha, P.A. Friedman, Advances and future directions in cardiac pacemakers, J. Am. Coll. Cardiol. 69 (2017) 211–235, http://dx.doi.org/10.1016/j.jacc.2016.10.064.
[179] S. Roundy, P.K. Wright, A piezoelectric vibration based generator for wireless electronics, Smart Mater. Struct. 13 (2004) 1131–1142, http://dx.doi.org/10.1088/0964-1726/13/5/018.
[180] H. Zhang, X.-S. Zhang, X. Cheng, Y. Liu, M. Han, X. Xue, S. Wang, F. Yang, S. A S, H. Zhang, Z. Xu, A flexible and implantable piezoelectric generator harvesting energy from the pulsation of ascending aorta: in vitro and in vivo studies, Nano Energy 12 (2015) 296–304, http://dx.doi.org/10.1016/j.nanoen.2014.12.038.
[181] L. Persano, C. Dagdeviren, Y. Su, Y. Zhang, S. Girardo, D. Pisignano, Y. Huang, J.A. Rogers, High performance piezoelectric devices based on aligned arrays of nanofibers of poly(vinylidenefluoride-co-trifluoroethylene), Nat. Commun. 4 (2013) 1633, http://dx.doi.org/10.1038/ncomms2639.
[182] K.-I. Park, S. Xu, Y. Liu, G.-T. Hwang, S.-J.L. Kang, Z.L. Wang, K.J. Lee, Piezoelectric BaTiO 3 thin film nanogenerator on plastic substrates, Nano Lett. 10 (2010) 4939–4943, http://dx.doi.org/10.1021/nl102959k.
[183] K.-I. Park, J.H. Son, G.-T. Hwang, C.K. Jeong, J. Ryu, M. Koo, I. Choi, S.H. Lee, M. Byun, Z.L. Wang, K.J. Lee, Highly-efficient, flexible piezoelectric PZT thin film nanogenerator on plastic substrates, Adv. Mater. 26 (2014) 2514–2520, http://dx.doi.org/10.1002/adma.201305659.
[184] C. Dagdeviren, Y. Su, P. Joe, R. Yona, Y. Liu, Y.S. Kim, Y. Huang, A.R. Damadoran, J. Xia, L.W. Martin, Y. Huang, J.A. Rogers, Conformable amplified lead zirconate titanate sensors with enhanced piezoelectric response for cutaneous pressure monitoring, Nat. Commun. 5 (2014) 1–10, http://dx.doi.org/10.1038/ncomms5496.
[185] Y. Qi, J. Kim, T.D. Nguyen, B. Lisko, P.K. Purohit, M.C. McAlpine, Enhanced piezoelectricity and Stretchability in energy harvesting devices fabricated from buckled PZT ribbons, Nano Lett. 11 (2011) 1331–1336, http://dx.doi.org/10.1021/nl104412b.
[186] C. Dagdeviren, Z. Li, Z.L. Wang, Energy harvesting from the animal/human body for self-powered electronics, Annu. Rev. Biomed. Eng. 19 (2017) 85–108, http://dx.doi.org/10.1146/annurev-bioeng-071516-044517.
[187] M.A. Parvez Mahmud, N. Huda, S.H. Farjana, M. Asadnia, C. Lang, Recent advances in Nanogenerator-driven self-powered implantable biomedical devices, Adv. Energy Mater. 1701210 (2017) 1701210, http://dx.doi.org/10.1002/aenm.201701210.
[188] N. Li, Z. Yi, Y. Ma, F. Xie, Y. Huang, Y. Tian, X. Dong, Y. Liu, X. Shao, Y. Li, L. Jin, J. Liu, Z. Xu, B. Yang, H. Zhang, Direct powering a real cardiac pacemaker by natural energy of a heartbeat, ACS Nano 13 (2019) 2822–2830, http://dx.doi.org/10.1021/acsnano.8b08567.
[189] Z. Yi, F. Xie, Y. Tian, N. Li, X. Dong, Y. Ma, Y. Huang, Y. Hu, X. Xu, D. Qu, X. Lang, Z. Xu, J. Liu, H. Zhang, B. Yang, A battery- and leadless heart-worn pacemaker strategy, Adv. Funct. Mater. 30 (2020) 2000477, http://dx.doi.org/10.1002/adfm.202000477.
[190] M. Deterre, E. Lefeuvre, Y. Zhu, M. Woytasik, B. Boutaud, R.D. Molin, Micro blood pressure energy harvester for intracardiac pacemaker, J. Microelectromech. Syst. 23 (2014) 651–660, http://dx.doi.org/10.1109/JMEMS.2013.2282623.
[191] Q. Shi, T. Wang, C. Lee, MEMS based broadband piezoelectric ultrasonic energy harvester (PUEH) for enabling self-powered implantable biomedical devices, Sci. Rep. 6 (2016) 24946, http://dx.doi.org/10.1038/srep24946.
[192] J. Wang, T. He, C. Lee, Development of neural interfaces and energy harvesters towards self-powered implantable systems for healthcare monitoring and rehabilitation purposes, Nano Energy 65 (2019) 104039, http://dx.doi.org/10.1016/j.nanoen.2019.104039.
[193] Q. Zheng, B. Shi, F. Fan, X. Wang, L. Yan, W. Yuan, S. Wang, H. Liu, Z. Li, Z.L. Wang, In vivo powering of pacemaker by breathing-driven implanted triboelectric nanogenerator, Adv. Mater. 26 (2014) 5851–5856, http://dx.doi.org/10.1002/adma.201402064.
[194] P. Song, S. Kuang, N. Panwar, G. Yang, D.J.H. Tng, S.C. Tjin, W.J. Ng, M.B.A. Majid, G. Zhu, K.T. Yong, Z.L. Wang, A self-powered implantable drug-delivery system using biokinetic energy, Adv. Mater. 29 (2017) 1–7, http://dx.doi.org/10.1002/adma.201605668.
[195] W. Tang, J. Tian, Q. Zheng, L. Yan, J. Wang, Z. Li, Z.L. Wang, Implantable self-powered low-level laser cure system for mouse embryonic osteoblasts' proliferation and differentiation, ACS Nano 9 (2015) 7867–7873, http://dx.doi.org/10.1021/acsnano.5b03567.
[196] C. Zhao, H. Feng, L. Zhang, Z. Li, Y. Zou, P. Tan, H. Ouyang, D. Jiang, M. Yu, C. Wang, H. Li, L. Xu, W. Wei, Z. Li, Highly efficient in vivo cancer therapy by an implantable magnet triboelectric nanogenerator, Adv. Funct. Mater. 29 (2019) 1–11, http://dx.doi.org/10.1002/adfm.201808640.
[197] S. Lee, H. Wang, W.Y. Xian Peh, T. He, S.C. Yen, N.V. Thakor, C. Lee, Mechano-neuromodulation of autonomic pelvic nerve for underactive bladder: a triboelectric neurostimulator integrated with flexible neural clip interface, Nano Energy 60 (2019) 449–456, http://dx.doi.org/10.1016/j.nanoen.2019.03.082.
[198] S. Lee, H. Wang, Q. Shi, L. Dhakar, J. Wang, N.V. Thakor, S.C. Yen, C. Lee, Development of battery-free neural interface and modulated control of tibialis anterior muscle via common peroneal nerve based on triboelectric nanogenerators (TENGs), Nano Energy 33 (2017) 1–11, http://dx.doi.org/10.1016/j.nanoen.2016.12.038.
[199] S. Lee, H. Wang, J. Wang, Q. Shi, S.C. Yen, N.V. Thakor, C. Lee, Battery-free neuromodulator for peripheral nerve direct stimulation, Nano Energy 50 (2018) 148–158, http://dx.doi.org/10.1016/j.nanoen.2018.04.004.
[200] R. Hinchet, H.-J. Yoon, H. Ryu, M.-K. Kim, E.-K. Choi, D.-S. Kim, S.-W. Kim, Transcutaneous ultrasound energy harvesting using capacitive triboelectric technology, Science (80-.) 365 (2019) 491–494, http://dx.doi.org/10.1126/science.aan3997.
[201] R. Wang, S. Gao, Z. Yang, Y. Li, W. Chen, B. Wu, W. Wu, Engineered and laser-processed chitosan biopolymers for sustainable and biodegradable triboelectric power generation, Adv. Mater. 30 (2018) 1706267, http://dx.doi.org/10.1002/adma.201706267.
[202] Z. Li, H. Feng, Q. Zheng, H. Li, C. Zhao, H. Ouyang, S. Noreen, M. Yu, F. Su, R. Liu, L. Li, Z.L. Wang, Z. Li, Photothermally tunable biodegradation of implantable triboelectric nanogenerators for tissue repairing, Nano Energy 54 (2018) 390–399, http://dx.doi.org/10.1016/j.nanoen.2018.10.020.
[203] Q. Zheng, Y. Zou, Y. Zhang, Z. Liu, B. Shi, X. Wang, Y. Jin, H. Ouyang, Z. Li, Z.L. Wang, Biodegradable triboelectric nanogenerator as a life-time designed implantable power source, Sci. Adv. 2 (2016) 1–10, http://dx.doi.org/10.1126/sciadv.1501478.
[204] W. Jiang, H. Li, Z. Liu, Z. Li, J. Tian, B. Shi, Y. Zou, H. Ouyang, C. Zhao, L. Zhao, R. Sun, H. Zheng, Y. Fan, Z.L. Wang, Z. Li, Fully bioabsorbable natural-materials-based triboelectric nanogenerators, Adv. Mater. 30 (2018) 1–10, http://dx.doi.org/10.1002/adma.201801895.
[205] Q. Guan, Y. Dai, Y. Yang, X. Bi, Z. Wen, Y. Pan, Near-infrared irradiation induced remote and efficient self-healable triboelectric nanogenerator for potential implantable electronics, Nano Energy 51 (2018) 333–339, http://dx.doi.org/10.1016/j.nanoen.2018.06.060.
[206] H. Ouyang, Z. Liu, N. Li, B. Shi, Y. Zou, F. Xie, Y. Ma, Z. Li, H. Li, Q. Zheng, X. Qu, Y. Fan, Z.L. Wang, H. Zhang, Z. Li, Symbiotic cardiac pacemaker, Nat. Commun. 10 (2019) 1821, http://dx.doi.org/10.1038/s41467-019-09851-1.
[207] Z.-D. Liu, J.-K. Liu, B. Wen, Q.-Y. He, Y. Li, F. Miao, Cuffless blood pressure estimation using pressure pulse wave signals, Sensors 18 (2018) 4227, http://dx.doi.org/10.3390/s18124227.
[208] T.-W. Wang, S.-F. Lin, Wearable piezoelectric-based system for continuous beat-to-beat blood pressure measurement, Sensors 20 (2020) 851, http://dx.doi.org/10.3390/s20030851.
[209] W. Wang, J. Cao, J. Yu, R. Liu, C.R. Bowen, W.-H. Liao, Self-powered smart insole for monitoring human gait signals, Sensors 19 (2019) 5336, http://dx.doi.org/10.3390/s19245336.
[210] A.M. Tahir, M.E.H. Chowdhury, A. Khandakar, S. Al-Hamouz, M. Abdalla, S. Awadallah, M.B.I. Reaz, N. Al-Emadi, A systematic approach to the design and characterization of a smart insole for detecting vertical ground reaction force (vGRF) in gait analysis, Sensors 20 (2020) 957, http://dx.doi.org/10.3390/s20040957.
[211] W. Guo, C. Tan, K. Shi, J. Li, X.-X. Wang, B. Sun, X. Huang, Y.-Z. Long, P. Jiang, Wireless piezoelectric devices based on electrospun PVDF/BaTiO 3 NW nanocomposite fibers for human motion monitoring, Nanoscale 10 (2018) 17751–17760, http://dx.doi.org/10.1039/C8NR05292A.
[212] D.Y. Park, D.J. Joe, D.H. Kim, H. Park, J.H. Han, C.K. Jeong, H. Park, J.G. Park, B. Joung, K.J. Lee, Self-powered real-time arterial pulse monitoring using ultrathin epidermal piezoelectric sensors, Adv. Mater. 29 (2017) 1702308, http://dx.doi.org/10.1002/adma.201702308.
[213] Z. Yi, H. Yang, Y. Tian, X. Dong, J. Liu, B. Yang, Self-powered force sensor based on thinned bulk PZT for real-time cutaneous activities monitoring, IEEE Electron Device Lett. 39 (2018) 1226–1229, http://dx.doi.org/10.1109/LED.2018.2846184.
[214] Z. Yi, J. Huang, Z. Liu, J. Liu, B. Yang, Portable, wireless wearable piezoelectric arterial pulse monitoring system based on near-field communication approach, IEEE Electron Device Lett. 41 (2020) 183–186, http://dx.doi.org/10.1109/LED.2019.2954878.
[215] C. Yan, W. Deng, L. Jin, T. Yang, Z. Wang, X. Chu, H. Su, J. Chen, W. Yang, Epidermis-inspired ultrathin 3D cellular sensor array for self-powered biomedical monitoring, ACS Appl. Mater. Interfaces 10 (2018) 41070–41075, http://dx.doi.org/10.1021/acsami.8b14514.
[216] M. Ha, S. Lim, J. Park, D.-S. Um, Y. Lee, H. Ko, Bioinspired interlocked and hierarchical design of ZnO nanowire arrays for static and dynamic

pressure-sensitive electronic skins, Adv. Funct. Mater. 25 (2015) 2841–2849, http://dx.doi.org/10.1002/adfm.201500453.
[217] Z. Chen, Z. Wang, X. Li, Y. Lin, N. Luo, M. Long, N. Zhao, J.-B. Xu, Flexible piezoelectric-induced pressure sensors for static measurements based on nanowires/graphene heterostructures, ACS Nano 11 (2017) 4507–4513, http://dx.doi.org/10.1021/acsnano.6b08027.
[218] S.K. Ghosh, P. Adhikary, S. Jana, A. Biswas, V. Sencadas, S.D. Gupta, B. Tudu, D. Mandal, Electrospun gelatin nanofiber based self-powered bio-e-skin for health care monitoring, Nano Energy 36 (2017) 166–175, http://dx.doi.org/10.1016/j.nanoen.2017.04.028.
[219] X. Gao, M. Zheng, X. Yan, J. Fu, M. Zhu, Y. Hou, The alignment of BCZT particles in PDMS boosts the sensitivity and cycling reliability of a flexible piezoelectric touch sensor, J. Mater. Chem. C 7 (2019) 961–967, http://dx.doi.org/10.1039/C8TC04741C.
[220] T. Bu, T. Xiao, Z. Yang, G. Liu, X. Fu, J. Nie, T. Guo, Y. Pang, J. Zhao, F. Xi, C. Zhang, Z.L. Wang, Stretchable triboelectric-photonic smart skin for tactile and gesture sensing, Adv. Mater. 30 (2018) 1800066, http://dx.doi.org/10.1002/adma.201800066.
[221] S. Chun, W. Son, H. Kim, S.K. Lim, C. Pang, C. Choi, Self-powered pressure- and vibration-sensitive tactile sensors for learning technique-based neural finger skin, Nano Lett. 19 (2019) 3305–3312, http://dx.doi.org/10.1021/acs.nanolett.9b00922.
[222] X.Z. Jiang, Y.J. Sun, Z. Fan, T.Y. Zhang, Integrated flexible, waterproof, transparent, and self-powered tactile sensing panel, ACS Nano 10 (2016) 7696–7704, http://dx.doi.org/10.1021/acsnano.6b03042.
[223] X. Wang, H. Zhang, L. Dong, X. Han, W. Du, J. Zhai, C. Pan, Z.L. Wang, Self-powered high-resolution and pressure-sensitive triboelectric sensor matrix for real-time tactile mapping, Adv. Mater. 28 (2016) 2896–2903, http://dx.doi.org/10.1002/adma.201503407.
[224] G. Zhu, W.Q. Yang, T. Zhang, Q. Jing, J. Chen, Y.S. Zhou, P. Bai, Z.L. Wang, Self-powered, ultrasensitive, flexible tactile sensors based on contact electrification, Nano Lett. 14 (2014) 3208–3213, http://dx.doi.org/10.1021/nl5005652.
[225] H. Guo, X. Pu, J. Chen, Y. Meng, M.-H. Yeh, G. Liu, Q. Tang, B. Chen, D. Liu, S. Qi, C. Wu, C. Hu, J. Wang, Z.L. Wang, A highly sensitive, self-powered triboelectric auditory sensor for social robotics and hearing aids, Sci. Robot. 3 (2018) eaat2516, http://dx.doi.org/10.1126/scirobotics.aat2516.
[226] Y. Xin, X. Qi, C. Qian, H. Tian, Z. Ling, Z. Jiang, A wearable respiration and pulse monitoring system based on PVDF piezoelectric film, Integr. Ferroelectr. 158 (2014) 43–51, http://dx.doi.org/10.1080/10584587.2014.957060.
[227] W. Dong, L. Xiao, W. Hu, C. Zhu, Y. Huang, Z. Yin, Wearable human–machine interface based on PVDF piezoelectric sensor, Trans. Inst. Meas. Control. 39 (2017) 398–403, http://dx.doi.org/10.1177/0142331216672918.
[228] J. Sato, T. Sekine, W. Yi-Fei, Y. Takeda, H. Matsui, D. Kumaki, F.D. Dos Santos, A. Miyabo, S. Tokito, Ferroelectric polymer-based fully printed flexible strain rate sensors and their application for human motion capture, Sensors Actuators A Phys. 295 (2019) 93–98, http://dx.doi.org/10.1016/j.sna.2019.05.022.
[229] S. You, H. Shi, J. Wu, L. Shan, S. Guo, S. Dong, A flexible, wave-shaped P(VDF-TrFE)/metglas piezoelectric composite for wearable applications, J. Appl. Phys. 120 (2016) 234103, http://dx.doi.org/10.1063/1.4972478.
[230] Y.K. Fuh, B.S. Wang, C.-Y. Tsai, Self-Powered Pressure Sensor with fully encapsulated 3D printed wavy substrate and highly-aligned piezoelectric fibers array, Sci. Rep. 7 (2017) 6759, http://dx.doi.org/10.1038/s41598-017-07360-z.
[231] Y. Xin, T. Liu, Y. Xu, J. Zhu, T. Lin, X. Zhou, Development of respiratory monitoring and actions recognition based on a pressure sensor with multi-arch structures, Sensors Actuators A Phys. 296 (2019) 357–366, http://dx.doi.org/10.1016/j.sna.2019.06.049.
[232] K. Van Volkinburg, G. Washington, Development of a wearable controller for gesture-recognition-based applications using polyvinylidene fluoride, IEEE Trans. Biomed. Circuits Syst. 11 (2017) 900–909, http://dx.doi.org/10.1109/TBCAS.2017.2683458.
[233] Y. Cha, J. Seo, J.-S. Kim, J.-M. Park, Human–computer interface glove using flexible piezoelectric sensors, Smart Mater. Struct. 26 (2017) 057002, http://dx.doi.org/10.1088/1361-665X/aa6b64.
[234] S. Lim, D. Son, J. Kim, Y.B. Lee, J.-K. Song, S. Choi, D.J. Lee, J.H. Kim, M. Lee, T. Hyeon, D.-H. Kim, Transparent and stretchable interactive human machine interface based on patterned graphene heterostructures, Adv. Funct. Mater. 25 (2015) 375–383, http://dx.doi.org/10.1002/adfm.201402987.
[235] C. Lü, S. Wu, B. Lu, Y. Zhang, Y. Du, X. Feng, Ultrathin flexible piezoelectric sensors for monitoring eye fatigue, J. Micromech. Microeng. 28 (2018) 025010, http://dx.doi.org/10.1088/1361-6439/aaa219.
[236] K.C. Pradel, W. Wu, Y. Ding, Z.L. Wang, Solution-derived ZnO homojunction nanowire films on wearable substrates for energy conversion and self-powered gesture recognition, Nano Lett. 14 (2014) 6897–6905, http://dx.doi.org/10.1021/nl5029182.
[237] M. Farooq, P. Chandler-Laney, M. Hernandez-Reif, E. Sazonov, Monitoring of infant feeding behavior using a jaw motion sensor, J. Healthc. Eng. 6 (2015) 23–40, http://dx.doi.org/10.1260/2040-2295.6.1.23.
[238] N. Alshurafa, H. Kalantarian, M. Pourhomayoun, J.J. Liu, S. Sarin, B. Shahbazi, M. Sarrafzadeh, Recognition of nutrition intake using time-frequency decomposition in a wearable necklace using a piezoelectric sensor, IEEE Sens. J. 15 (2015) 3909–3916, http://dx.doi.org/10.1109/JSEN.2015.2402652.
[239] H. Kalantarian, N. Alshurafa, T. Le, M. Sarrafzadeh, Monitoring eating habits using a piezoelectric sensor-based necklace, Comput. Biol. Med. 58 (2015) 46–55, http://dx.doi.org/10.1016/j.compbiomed.2015.01.005.
[240] H. Kalantarian, B. Motamed, N. Alshurafa, M. Sarrafzadeh, A wearable sensor system for medication adherence prediction, Artif. Intell. Med. 69 (2016) 43–52, http://dx.doi.org/10.1016/j.artmed.2016.03.004.
[241] G. Hussain, K. Javed, J. Cho, J. Yi, Food intake detection and classification using a necklace-type piezoelectric wearable sensor system, IEICE Trans. Inf. Syst. E101.D (2018) 2795–2807, http://dx.doi.org/10.1587/transinf.2018EDP7076.
[242] M. Farooq, E. Sazonov, A novel wearable device for food intake and physical activity recognition, Sensors 16 (2016) 1067, http://dx.doi.org/10.3390/s16071067.
[243] M. Yoshida, K. Onishi, K. Tanimoto, S. Nishikawa, Flexible tension sensor based on poly(l-lactic acid) film with coaxial structure, J. Appl. Phys. 56 (2017), 10PG02, http://dx.doi.org/10.7567/JJAP.56.10PG02.
[244] H. Hu, X. Zhu, C. Wang, L. Zhang, X. Li, S. Lee, Z. Huang, R. Chen, Z. Chen, C. Wang, Y. Gu, Y. Chen, Y. Lei, T. Zhang, N. Kim, Y. Guo, Y. Teng, W. Zhou, Y. Li, A. Nomoto, S. Sternini, Q. Zhou, M. Pharr, F.L. di Scalea, S. Xu, Stretchable ultrasonic transducer arrays for three-dimensional imaging on complex surfaces, Sci. Adv. 4 (2018) eaar3979, http://dx.doi.org/10.1126/sciadv.aar3979.
[245] C. Wang, X. Li, H. Hu, L. Zhang, Z. Huang, M. Lin, Z. Zhang, Z. Yin, B. Huang, H. Gong, S. Bhaskaran, Y. Gu, M. Makihata, Y. Guo, Y. Lei, Y. Chen, C. Wang, Y. Li, T. Zhang, Z. Chen, A.P. Pisano, L. Zhang, Q. Zhou, S. Xu, Monitoring of the central blood pressure waveform via a conformal ultrasonic device, Nat. Biomed. Eng. 2 (2018) 687–695, http://dx.doi.org/10.1038/s41551-018-0287-x.
[246] S.-W. Kim, Y. Lee, J. Park, S. Kim, H. Chae, H. Ko, J. Kim, A triple-mode flexible E-skin sensor interface for multi-purpose wearable applications, Sensors 18 (2017) 78, http://dx.doi.org/10.3390/s18010078.
[247] H.J. Qiu, W.Z. Song, X.X. Wang, J. Zhang, Z. Fan, M. Yu, S. Ramakrishna, Y.Z. Long, A calibration-free self-powered sensor for vital sign monitoring and finger tap communication based on wearable triboelectric nanogenerator, Nano Energy 58 (2019) 536–542, http://dx.doi.org/10.1016/j.nanoen.2019.01.069.
[248] H. Ouyang, J. Tian, G. Sun, Y. Zou, Z. Liu, H. Li, L. Zhao, B. Shi, Y. Fan, Y. Fan, Z.L. Wang, Z. Li, Self-powered pulse sensor for antidiastole of cardiovascular disease, Adv. Mater. 29 (2017) 1–10, http://dx.doi.org/10.1002/adma.201703456.
[249] X. Li, Z.-H. Lin, G. Cheng, X. Wen, Y. Liu, S. Niu, Z.L. Wang, 3D fiber-based hybrid nanogenerator for energy harvesting and as a self-powered pressure sensor, ACS Nano 8 (2014) 10674–10681, http://dx.doi.org/10.1021/nn504243j.
[250] W. Xu, L.B. Huang, M.C. Wong, L. Chen, G. Bai, J. Hao, Environmentally friendly hydrogel-based triboelectric nanogenerators for versatile energy harvesting and self-powered sensors, Adv. Energy Mater. 7 (2017) 1–8, http://dx.doi.org/10.1002/aenm.201601529.
[251] L. Jin, J. Tao, R. Bao, L. Sun, C. Pan, Self-powered real-time movement monitoring sensor using triboelectric nanogenerator technology, Sci. Rep. 7 (2017) 10521, http://dx.doi.org/10.1038/s41598-017-10990-y.
[252] F. Yi, Z. Zhang, Z. Kang, Q. Liao, Y. Zhang, Recent advances in triboelectric nanogenerator-based health monitoring, Adv. Funct. Mater. 29 (2019) 1–16, http://dx.doi.org/10.1002/adfm.201808849.
[253] D.L. Wen, X. Liu, H.T. Deng, D.H. Sun, H.Y. Qian, J. Brugger, X.S. Zhang, Printed silk-fibroin-based triboelectric nanogenerators for multi-functional wearable sensing, Nano Energy 66 (2019) 104123, http://dx.doi.org/10.1016/j.nanoen.2019.104123.
[254] Y. Liu, L. Wang, L. Zhao, K. Yao, Z. Xie, Y. Zi, X. Yu, Thin, Skin-Integrated, Stretchable Triboelectric Nanogenerators for Tactile Sensing, Adv. Electron. Mater. 6 (2020) 1–7, http://dx.doi.org/10.1002/aelm.201901174.
[255] X. Wang, Y. Zhang, X. Zhang, Z. Huo, X. Li, M. Que, Z. Peng, H. Wang, C. Pan, A highly stretchable transparent self-powered triboelectric tactile sensor with metallized nanofibers for wearable electronics, Adv. Mater. 30 (2018) 1706738, http://dx.doi.org/10.1002/adma.201706738.
[256] T. Chen, Q. Shi, M. Zhu, T. He, L. Sun, L. Yang, C. Lee, Triboelectric self-powered wearable flexible patch as 3D motion control interface for robotic manipulator, ACS Nano 12 (2018), http://dx.doi.org/10.1021/acsnano.8b06747.
[257] Q. Shi, C. Qiu, T. He, F. Wu, M. Zhu, J.A. Dziuban, R. Walczak, M.R. Yuce, C. Lee, Triboelectric single-electrode-output control interface using patterned grid electrode, Nano Energy 60 (2019) 545–556, http://dx.doi.org/10.1016/j.nanoen.2019.03.090.
[258] Z. Lin, Z. Wu, B. Zhang, Y.-C. Wang, H. Guo, G. Liu, C. Chen, Y. Chen, J. Yang, Z.L. Wang, A triboelectric nanogenerator-based smart insole for multifunctional gait monitoring, Int. J. Adv. Mater. Technol. 1800360 (2018) 1800360, http://dx.doi.org/10.1002/admt.201800360.
[259] X. Pu, H. Guo, J. Chen, X. Wang, Y. Xi, C. Hu, Z.L. Wang, Eye motion triggered self-powered mechnosensational communication system using triboelectric nanogenerator, Sci. Adv. 3 (2017) 1–8, http://dx.doi.org/10.1126/sciadv.1700694.
[260] J. Yang, J. Chen, Y. Su, Q. Jing, Z. Li, F. Yi, X. Wen, Z. Wang, Z.L. Wang, Eardrum-inspired active sensors for self-powered cardiovascular system characterization and throat-attached anti-interference voice recognition, Adv. Mater. 27 (2015) 1316–1326, http://dx.doi.org/10.1002/adma.201404794.

[261] J. Yang, J. Chen, Y. Liu, W. Yang, Y. Su, Z.L. Wang, Triboelectrification-based organic film nanogenerator for acoustic energy harvesting and self-powered active acoustic sensing, ACS Nano 8 (2014) 2649–2657, http://dx.doi.org/10.1021/nn4063616.
[262] P. Maharjan, R.M. Toyabur, J.Y. Park, A human locomotion inspired hybrid nanogenerator for wrist-wearable electronic device and sensor applications, Nano Energy 46 (2018) 383–395, http://dx.doi.org/10.1016/j.nanoen.2018.02.033.
[263] Y. Han, F. Yi, C. Jiang, K. Dai, Y. Xu, X. Wang, Z. You, Self-powered gait pattern-based identity recognition by a soft and stretchable triboelectric band, Nano Energy 56 (2019) 516–523, http://dx.doi.org/10.1016/j.nanoen.2018.11.078.
[264] F. Yi, L. Lin, S. Niu, P.K. Yang, Z. Wang, J. Chen, Y. Zhou, Y. Zi, J. Wang, Q. Liao, Y. Zhang, Z.L. Wang, Stretchable-rubber-based triboelectric nanogenerator and its application as self-powered body motion sensors, Adv. Funct. Mater. 25 (2015) 3688–3696, http://dx.doi.org/10.1002/adfm.201500428.
[265] Z. Su, H. Wu, H. Chen, H. Guo, X. Cheng, Y. Song, X. Chen, H. Zhang, Digitalized self-powered strain gauge for static and dynamic measurement, Nano Energy 42 (2017) 129–137, http://dx.doi.org/10.1016/j.nanoen.2017.10.004.
[266] X. Pu, H. Guo, Q. Tang, J. Chen, L. Feng, G. Liu, X. Wang, Y. Xi, C. Hu, Z.L. Wang, Rotation sensing and gesture control of a robot joint via triboelectric quantization sensor, Nano Energy 54 (2018) 453–460, http://dx.doi.org/10.1016/j.nanoen.2018.10.044.
[267] M. Zhu, Z. Sun, Z. Zhang, Q. Shi, T. He, H. Liu, T. Chen, C. Lee, Haptic-feedback smart glove as a creative human-machine interface (HMI) for virtual/augmented reality applications, Sci. Adv. 6 (2020) eaaz8693, http://dx.doi.org/10.1126/sciadv.aaz8693.
[268] Y.-C. Lai, J. Deng, S.L. Zhang, S. Niu, H. Guo, Z.L. Wang, Single-thread-Based wearable and highly stretchable triboelectric nanogenerators and their applications in cloth-based self-powered human-interactive and biomedical sensing, Adv. Funct. Mater. 27 (2017) 1604462, http://dx.doi.org/10.1002/adfm.201604462.
[269] S.B. Jeon, W.G. Kim, S.J. Park, I.W. Tcho, I.K. Jin, J.K. Han, D. Kim, Y.K. Choi, Self-powered wearable touchpad composed of all commercial fabrics utilizing a crossline array of triboelectric generators, Nano Energy 65 (2019) 103994, http://dx.doi.org/10.1016/j.nanoen.2019.103994.
[270] C. Chen, L. Chen, Z. Wu, H. Guo, W. Yu, Z. Du, Z.L. Wang, 3D double-faced interlock fabric triboelectric nanogenerator for bio-motion energy harvesting and as self-powered stretching and 3D tactile sensors, Mater. Today. 32 (2020) 84–93, http://dx.doi.org/10.1016/j.mattod.2019.10.025.
[271] L. Ma, M. Zhou, R. Wu, A. Patil, H. Gong, S. Zhu, T. Wang, Continuous and Scalable Manufacture of Hybridized Nano-Micro Triboelectric Yarns for Energy Harvesting and Signal Sensing, 2020, http://dx.doi.org/10.1021/acsnano.0c00524.
[272] F. Wen, Z. Sun, T. He, Q. Shi, M. Zhu, Z. Zhang, L. Li, T. Zhang, C. Lee, Machine learning glove using self-powered conductive superhydrophobic triboelectric textile for gesture recognition in VR/AR applications, Adv. Sci. 7 (2020) 2000261, http://dx.doi.org/10.1002/advs.202000261.
[273] B. Dong, Q. Shi, T. He, S. Zhu, Z. Zhang, Z. Sun, Y. Ma, D. Kwong, C. Lee, Wearable triboelectric/aluminum nitride nano-energy-nano-system with self-sustainable photonic modulation and continuous force sensing, Adv. Sci. 7 (2020) 1903636, http://dx.doi.org/10.1002/advs.201903636.
[274] B. Dong, Y. Yang, Q. Shi, S. Xu, Z. Sun, S. Zhu, Z. Zhang, D.-L. Kwong, G. Zhou, K.-W. Ang, C. Lee, Wearable triboelectric–human–machine interface (THMI) using robust nanophotonic readout, ACS Nano (2020), http://dx.doi.org/10.1021/acsnano.0c03728, acsnano.0c03728.
[275] C. Dagdeviren, F. Javid, P. Joe, T. von Erlach, T. Bensel, Z. Wei, S. Saxton, C. Cleveland, L. Booth, S. McDonnell, J. Collins, A. Hayward, R. Langer, G. Traverso, Flexible piezoelectric devices for gastrointestinal motility sensing, Nat. Biomed. Eng. 1 (2017) 807–817, http://dx.doi.org/10.1038/s41551-017-0140-7.
[276] W. Zhang, L. Zhang, H. Gao, W. Yang, S. Wang, L. Xing, X. Xue, Self-powered implantable skin-like glucometer for real-time detection of blood glucose level in vivo, Nano-Micro Lett. 10 (2018) 32, http://dx.doi.org/10.1007/s40820-017-0185-x.
[277] Z. Liu, Y. Ma, H. Ouyang, B. Shi, N. Li, D. Jiang, F. Xie, D. Qu, Y. Zou, Y. Huang, H. Li, C. Zhao, P. Tan, M. Yu, Y. Fan, H. Zhang, Z.L. Wang, Z. Li, Transcatheter Self-Powered Ultrasensitive Endocardial Pressure Sensor, Adv. Funct. Mater. 29 (2019) 1–10, http://dx.doi.org/10.1002/adfm.201807560.
[278] J.-H. Park, D. Jang, J. Park, S. Youm, Wearable sensing of in-ear pressure for heart rate monitoring with a piezoelectric sensor, Sensors 15 (2015) 23402–23417, http://dx.doi.org/10.3390/s150923402.
[279] K.-Y. Shin, J.S. Lee, J. Jang, Highly sensitive, wearable and wireless pressure sensor using free-standing ZnO nanoneedle/PVDF hybrid thin film for heart rate monitoring, Nano Energy 22 (2016) 95–104, http://dx.doi.org/10.1016/j.nanoen.2016.02.012.
[280] R. Meier, N. Kelly, O. Almog, P. Chiang, A piezoelectric energy-harvesting shoe system for podiatric sensing, in: 2014 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc., IEEE, 2014, pp. 622–625, http://dx.doi.org/10.1109/EMBC.2014.6943668.
[281] K. Song, S.H. Kim, S. Jin, S. Kim, S. Lee, J.-S. Kim, J.-M. Park, Y. Cha, Pneumatic actuator and flexible piezoelectric sensor for soft virtual reality glove system, Sci. Rep. 9 (2019) 8988, http://dx.doi.org/10.1038/s41598-019-45422-6.
[282] S. Wang, X. Mu, Y. Yang, C. Sun, A.Y. Gu, Z.L. Wang, Flow-driven triboelectric generator for directly powering a wireless sensor node, Adv. Mater. 27 (2015) 240–248, http://dx.doi.org/10.1002/adma.201403944.
[283] Z. Lin, Q. He, Y. Xiao, T. Zhu, J. Yang, C. Sun, Z. Zhou, H. Zhang, Z. Shen, J. Yang, Z.L. Wang, Flexible timbo-like triboelectric nanogenerator as self-powered force and bend sensor for wireless and distributed landslide monitoring, Adv. Mater. Technol. 3 (2018) 1–9, http://dx.doi.org/10.1002/admt.201800144.
[284] K.W. Lim, M. Peddigari, C.H. Park, H.Y. Lee, Y. Min, J.W. Kim, C.W. Ahn, J.J. Choi, B.D. Hahn, J.H. Choi, D.S. Park, J.K. Hong, J.T. Yeom, W.H. Yoon, J. Ryu, S.N. Yi, G.T. Hwang, A high output magneto-mechano-triboelectric generator enabled by accelerated water-soluble nano-bullets for powering a wireless indoor positioning system, Energy Environ. Sci. 12 (2019) 666–674, http://dx.doi.org/10.1039/c8ee03008a.
[285] B.D. Chen, W. Tang, C. He, C.R. Deng, L.J. Yang, L.P. Zhu, J. Chen, J.J. Shao, L. Liu, Z.L. Wang, Water wave energy harvesting and self-powered liquid-surface fluctuation sensing based on bionic-jellyfish triboelectric nanogenerator, Mater. Today. 21 (2018) 88–97, http://dx.doi.org/10.1016/j.mattod.2017.10.006.
[286] Z. Zhou, X. Li, Y. Wu, H. Zhang, Z. Lin, K. Meng, Z. Lin, Q. He, C.C. Sun, J. Yang, Z.L. Wang, Wireless self-powered sensor networks driven by triboelectric nanogenerator for in-situ real time survey of environmental monitoring, Nano Energy 53 (2018) 501–507, http://dx.doi.org/10.1016/j.nanoen.2018.08.055.
[287] H. Yang, M. Wang, M. Deng, H. Guo, W. Zhang, H. Yang, Y. Xi, X. Li, C. Hu, Z. Wang, A full-packaged rolling triboelectric-electromagnetic hybrid nanogenerator for energy harvesting and building up self-powered wireless systems, Nano Energy 56 (2019) 300–306, http://dx.doi.org/10.1016/j.nanoen.2018.11.043.
[288] L. Jin, W. Deng, Y. Su, Z. Xu, H. Meng, B. Wang, H. Zhang, B. Zhang, L. Zhang, X. Xiao, M. Zhu, W. Yang, Self-powered wireless smart sensor based on maglev porous nanogenerator for train monitoring system, Nano Energy 38 (2017) 185–192, http://dx.doi.org/10.1016/j.nanoen.2017.05.018.
[289] Y.L. Chen, D. Liu, S. Wang, Y.F. Li, X.S. Zhang, Self-powered smart active RFID tag integrated with wearable hybrid nanogenerator, Nano Energy 64 (2019) 103911, http://dx.doi.org/10.1016/j.nanoen.2019.103911.
[290] H. Zhang, J. Wang, Y. Xie, G. Yao, Z. Yan, L. Huang, S. Chen, T. Pan, L. Wang, Y. Su, W. Yang, Y. Lin, Self, -Powered, wireless, remote meteorologic monitoring based on triboelectric nanogenerator operated by scavenging wind energy, ACS Appl. Mater. Interfaces 8 (2016) 32649–32654, http://dx.doi.org/10.1021/acsami.6b12798.
[291] B. Zhang, J. Chen, L. Jin, W. Deng, L. Zhang, H. Zhang, M. Zhu, W. Yang, Z.L. Wang, Rotating-disk-Based hybridized electromagnetic-triboelectric nanogenerator for sustainably powering wireless traffic volume sensors, ACS Nano 10 (2016) 6241–6247, http://dx.doi.org/10.1021/acsnano.6b02384.
[292] K. Zhao, Z.L. Wang, Y. Yang, Self-powered wireless smart sensor node enabled by an ultrastable, highly efficient, and superhydrophobic-surface-Based triboelectric nanogenerator, ACS Nano 10 (2016) 9044–9052, http://dx.doi.org/10.1021/acsnano.6b05815.
[293] X. Cao, M. Zhang, J. Huang, T. Jiang, J. Zou, N. Wang, Z.L. Wang, Inductor-free wireless energy delivery via maxwell's displacement current from an electrodeless triboelectric nanogenerator, Adv. Mater. 30 (2018) 1–8, http://dx.doi.org/10.1002/adma.201704077.
[294] Y. Jie, J. Ma, Y. Chen, X. Cao, N. Wang, Z.L. Wang, Efficient delivery of power generated by a rotating triboelectric nanogenerator by conjunction of wired and wireless transmissions using Maxwell's displacement currents, Adv. Energy Mater. 8 (2018) 1–7, http://dx.doi.org/10.1002/aenm.201802084.
[295] M.H. Yeh, L. Lin, P.K. Yang, Z.L. Wang, Motion-driven electrochromic reactions for self-powered smart window system, ACS Nano 9 (2015) 4757–4765, http://dx.doi.org/10.1021/acsnano.5b00706.
[296] Y. Chen, Y. Cheng, Y. Jie, X. Cao, N. Wang, Z.L. Wang, Energy harvesting and wireless power transmission by a hybridized electromagnetic-triboelectric nanogenerator, Energy Environ. Sci. 12 (2019) 2678–2684, http://dx.doi.org/10.1039/c9ee01245a.
[297] J. Zhu, H. Wang, Z. Zhang, Z. Ren, Q. Shi, W. Liu, C. Lee, Continuous direct current by charge transportation for next-generation IoT and real-time virtual reality applications, Nano Energy 73 (2020) 104760, http://dx.doi.org/10.1016/j.nanoen.2020.104760.
[298] G. Liu, J. Chen, Q. Tang, L. Feng, H. Yang, J. Li, Y. Xi, X. Wang, C. Hu, Wireless electric energy transmission through various isolated solid media based on triboelectric nanogenerator, Adv. Energy Mater. 8 (2018) 1–7, http://dx.doi.org/10.1002/aenm.201703086.
[299] Y. Zou, P. Tan, B. Shi, H. Ouyang, D. Jiang, Z. Liu, H. Li, M. Yu, C. Wang, X. Qu, L. Zhao, Y. Fan, Z.L. Wang, Z. Li, A bionic stretchable nanogenerator for underwater sensing and energy harvesting, Nat. Commun. 10 (2019) 1–10, http://dx.doi.org/10.1038/s41467-019-10433-4.
[300] W. Yin, Y. Xie, J. Long, P. Zhao, J. Chen, J. Luo, X. Wang, S. Dong, A self-power-transmission and non-contact-reception keyboard based on a novel resonant triboelectric nanogenerator (R-TENG), Nano Energy 50 (2018) 16–24, http://dx.doi.org/10.1016/j.nanoen.2018.05.009.
[301] J. Chen, W. Xuan, P. Zhao, U. Farooq, P. Ding, W. Yin, H. Jin, X. Wang, Y. Fu, S. Dong, J. Luo, Triboelectric effect based instantaneous self-powered wireless sensing with self-determined identity, Nano Energy 51 (2018) 1–9, http://dx.doi.org/10.1016/j.nanoen.2018.06.029.

[302] A. Ahmed, S.L. Zhang, I. Hassan, Z. Saadatnia, Y. Zi, J. Zu, Z.L. Wang, A washable, stretchable, and self-powered human-machine interfacing Triboelectric nanogenerator for wireless communications and soft robotics pressure sensor arrays, Extrem. Mech. Lett. 13 (2017) 25–35, http://dx.doi.org/10.1016/j.eml.2017.01.006.
[303] J. Huang, X. Yang, J. Yu, J. Han, C. Jia, M. Ding, J. Sun, X. Cao, Q. Sun, Z.L. Wang, A universal and arbitrary tactile interactive system based on self-powered optical communication, Nano Energy 69 (2020) 104419, http://dx.doi.org/10.1016/j.nanoen.2019.104419.
[304] S. Kang, S. Cho, R. Shanker, H. Lee, J. Park, D.S. Um, Y. Lee, H. Ko, Transparent and conductive nanomembranes with orthogonal silver nanowire arrays for skin-attachable loudspeakers and microphones, Sci. Adv. 4 (2018) 1–12, http://dx.doi.org/10.1126/sciadv.aas8772.
[305] M. Han, X. Chen, B. Yu, H. Zhang, Coupling of piezoelectric and triboelectric effects: from theoretical analysis to experimental verification, Adv. Electron. Mater. 1 (2015) 1–12, http://dx.doi.org/10.1002/aelm.201500187.
[306] X. Wang, B. Yang, J. Liu, Y. Zhu, C. Yang, Q. He, A flexible triboelectric-piezoelectric hybrid nanogenerator based on P(VDF-TrFE) nanofibers and PDMS/MWCNT for wearable devices, Sci. Rep. 6 (2016) 1–10, http://dx.doi.org/10.1038/srep36409.
[307] X. Wang, B. Yang, J. Liu, C. Yang, A transparent and biocompatible single-friction-surface triboelectric and piezoelectric generator and body movement sensor, J. Mater. Chem. A 5 (2017) 1176–1183, http://dx.doi.org/10.1039/C6TA09501A.
[308] S. Qin, Q. Zhang, X. Yang, M. Liu, Q. Sun, Z.L. Wang, Hybrid Piezo/triboelectric-driven self-charging electrochromic supercapacitor power package, Adv. Energy Mater. 8 (2018) 1–9, http://dx.doi.org/10.1002/aenm.201800069.
[309] X. He, Y. Zi, H. Yu, S.L. Zhang, J. Wang, W. Ding, H. Zou, W. Zhang, C. Lu, Z.L. Wang, An ultrathin paper-based self-powered system for portable electronics and wireless human-machine interaction, Nano Energy 39 (2017) 328–336, http://dx.doi.org/10.1016/j.nanoen.2017.06.046.
[310] J. Chung, H. Yong, H. Moon, Q. Van Duong, S.T. Choi, D. Kim, S. Lee, Hand-driven gyroscopic hybrid nanogenerator for recharging portable devices, Adv. Sci. 5 (2018), http://dx.doi.org/10.1002/advs.201801054.
[311] H. Qin, G. Cheng, Y. Zi, G. Gu, B. Zhang, W. Shang, F. Yang, J. Yang, Z. Du, Z.L. Wang, High energy storage efficiency triboelectric nanogenerators with unidirectional switches and passive power management circuits, Adv. Funct. Mater. 1805216 (2018) 1805216, http://dx.doi.org/10.1002/adfm.201805216.
[312] S. Xu, W. Ding, H. Guo, X. Wang, Z.L. Wang, Boost the performance of triboelectric nanogenerators through circuit oscillation, Adv. Energy Mater. 1900772 (2019) 1900772, http://dx.doi.org/10.1002/aenm.201900772.
[313] J. Chun, B.U. Ye, J.W. Lee, D. Choi, C.Y. Kang, S.W. Kim, Z.L. Wang, J.M. Baik, Boosted output performance of triboelectric nanogenerator via electric double layer effect, Nat. Commun. 7 (2016) 1–9, http://dx.doi.org/10.1038/ncomms12985.
[314] W. Liu, Z. Wang, G. Wang, G. Liu, J. Chen, X. Pu, Y. Xi, X. Wang, H. Guo, C. Hu, Z.L. Wang, Integrated charge excitation triboelectric nanogenerator, Nat. Commun. 10 (2019) 1–9, http://dx.doi.org/10.1038/s41467-019-09464-8.
[315] Y. Liu, W. Liu, Z. Wang, W. He, Q. Tang, Y. Xi, X. Wang, H. Guo, C. Hu, Quantifying contact status and the air-breakdown model of charge-excitation triboelectric nanogenerators to maximize charge density, Nat. Commun. 11 (2020) 1599, http://dx.doi.org/10.1038/s41467-020-15368-9.
[316] F. Wen, H. Wang, T. He, Q. Shi, Z. Sun, M. Zhu, Z. Zhang, Z. Cao, Y. Dai, T. Zhang, C. Lee, Battery-free short-range self-powered wireless sensor network (SS-WSN) using TENG based direct sensory transmission (TDST) mechanism, Nano Energy 67 (2020) 104266, http://dx.doi.org/10.1016/j.nanoen.2019.104266.
[317] S. Lee, C. Lee, Toward advanced neural interfaces for the peripheral nervous system (PNS) and their future applications, Curr. Opin. Biomed. Eng. 6 (2018) 130–137, http://dx.doi.org/10.1016/j.cobme.2018.05.004.
[318] Z.L. Wang, J. Chen, L. Lin, Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors, Energy Environ. Sci. 8 (2015) 2250–2282, http://dx.doi.org/10.1039/c5ee01532d.
[319] Z. Wang, W. Liu, J. Hu, W. He, H. Yang, C. Ling, Y. Xi, X. Wang, A. Liu, C. Hu, Two voltages in contact-separation triboelectric nanogenerator: from asymmetry to symmetry for maximum output, Nano Energy 69 (2020), http://dx.doi.org/10.1016/j.nanoen.2020.104452.
[.2320] X. Xia, H. Wang, P. Basset, Y. Zhu, Y. Zi, Inductor-free output multiplier for power promotion and management of triboelectric nanogenerators toward self-powered systems, ACS appl. Mater. Interfaces. 12 (2020) 5892–5900, http://dx.doi.org/10.1021/acsami.9b20060.
[321] W. Liu, Z. Wang, G. Wang, Q. Zeng, W. He, L. Liu, X. Wang, Y. Xi, H. Guo, C. Hu, Z.L. Wang, Switched-capacitor-convertors based on fractal design for output power management of triboelectric nanogenerator, Nat. Commun. 11 (2020) 1–10, http://dx.doi.org/10.1038/s41467-020-15373-y.
[322] S. Xu, L. Zhang, W. Ding, H. Guo, X. Wang, Z. Lin, Nano Energy self-doubled-rectification of triboelectric nanogenerator, Nano Energy (2019) 104165, http://dx.doi.org/10.1016/j.nanoen.2019.104165.
[323] C. Dagdeviren, The future of bionic dynamos, Science (80-.) 354 (2016) 1109, http://dx.doi.org/10.1126/science.aal2190.
[324] J. Zhu, M. Zhu, Q. Shi, F. Wen, L. Liu, B. Dong, A. Haroun, Y. Yang, P. Vachon, X. Guo, T. He, C. Lee, Progress in TENG technology—A journey from energy harvesting to nanoenergy and nanosystem, EcoMat (2020) 1–45, http://dx.doi.org/10.1002/eom2.12058.

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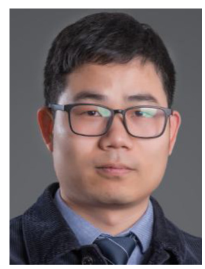

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