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Review

All-in-one self-powered flexible microsystems based on triboelectric nanogenerators

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ABSTRACT

Wearable electronics experienced a blooming prosperity in the past decade due to their trend of miniaturization and smart functions integration, and the appealing intrinsic physical properties, such as flexibility, stretchability, and conformability. Although wearable electronics play an important role in modern society, either as sensing devices for information collection or as mobile terminates for data exchange, further wider applications essentially require overcoming the restriction of traditional rigid, unsustainable power sources, thereby promoting the favorable properties of stability, high-output, maintenance-free, flexibility and also stretchability for the most sophisticated wearable electronics. Moreover, an attractive future vision of the development of wearable electronics is to integrate discrete components, including but not limited to sensors, actuators, integrated circuits and power sources, in order to realize self-powered flexible microsystems. Quantitative comparison and qualitative analysis prove that emerging triboelectric nanogenerators (TENGs) represents a powerful and promising approach to address the challenges above. TENGs, which scavenge the mechanical energy from ambient environment based on the combination of contact electrification and electrostatic induction, have been demonstrated to be a robust power source for a diverse set of applications. Furthermore, a new concept of self-powered system exploits the electricity generated by TENG to directly provide the power supply to other functional parts of the system. An additional option of self-powered system involves utilizing the quantitative relation between electrical signals and environmental changes to realize active sensors. Here, this paper reviews the feasibility of “all-in-one” self-powered flexible microsystems by introducing the technology of TENG around the following major categories: working principles, advanced materials, TENG-based active sensors, TENG-powered actuators, and integrated microsystems.

1. Introduction

In the past decades, the rapidly advancing development of micro/nano fabrication technology promoted electronics into a smart era towards ultra-miniaturization, multiple functionalization, and super-integration [1–3]. Moreover, the great innovation of advanced materials endows electronics with unique skin-like properties such as flexibility and stretchablility, thereby enabling wearable electronics [4–6]. Together with Internet of Things (IoT) [7], artificial Intelligence [8] and other emerging applications, wearable electronics [9] have attracted intensive attentions in the past ten years not only in laboratory research bus also increasingly in industrial for real-life applications. The global market of wearable electronics technology is expected to reach an estimated over $150 billion by 2026 and was forecasted to grow at an annual rate of 23% from 2018 to 2023 [10]. Smart wearable electronics begin to be widely distributed in almost all aspects of daily life of human beings, including personal health and fitness, portable communication and security, mobile entertainment and many others. However, there are still several critical challenges for wider applications. The most challenging one and ultimate goal is to provide a power source that can possess sufficient power density to sustain the operation of the wearable, has in addition remarkable flexibility and stretchability, as well as biocompatibility [11,12]. Battery is still the first-order choice until now but with obvious drawbacks, such as cyclically recharging, periodical maintenance and replacement and biological incompatibility.

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One promising approach to respond to the above issue is energy harvesting from the living environment, especially from the human body where hundreds of watts can be generated by physical motion and heat emission [13,14]. Several techniques have been proposed to transform these abundant energy sources into electricity, including photovoltaic effect [15], thermoelectric effect [16], electromagnetic effect [17], piezoelectric effect [18] and triboelectric effect [19], which are comprehensively reviewed and their key characterizations benchmarked in the section of technical progress. Among them, triboelectric nanogenerator (TENG), an emerging technique firstly reported in 2012 [19], has been demonstrated to be a robust power source, and exhibits more attractive potential due to its outstanding characterizations of sustainability, high-output performance, and unrestricted material selection [20–24]. Moreover, TENG allows for a distinctive feature of powering integrated electronics to realize self-powered system, or serving as an active sensor attributed to the quantitative relation between electrical output and ambient input [23,25–28].

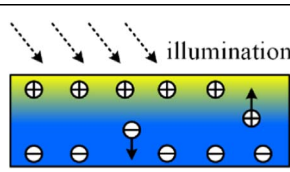
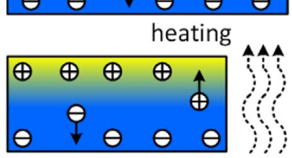
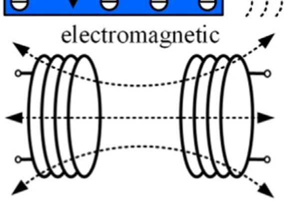
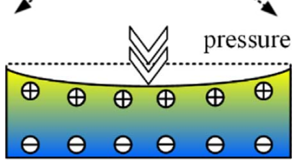
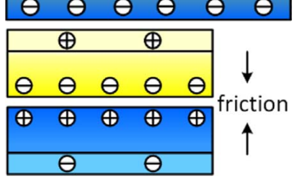
Therefore, TENGs provide the possibility of serving as both sustainable power sources and active sensors simultaneously, which creates a new blueprint of self-powered flexible microsystems that can sense, process and respond to the environmental changes with no need for external power source. These environmental changes could be ambient factors, e.g. humidity, temperature, pressure, and also biological information, e.g. body temperature, blood pressure, heart beating rate. Several prototypes have been developed to demonstrate the above schemes, which are summarized in the section of progress of TENG. Finally, we portray an "All-in-One" self-powered flexible microsystem as the future vision of smart wearable electronics.

2. Technical progress

Harvesting energy from the living environment is a promising approach to meet the energy demand of internet-of-things microsystems based on low-power-electronics. It shows attractive potential to realize fully-integrated self-powered devices without the need to replace batteries or to lay out long wires to a power supply. Several techniques have been developed by previous research work, such as photoelectric conversion, piezoelectric effect, thermoelectric effect, biochemical reactions, and so on. These techniques can be employed to harvest the ambient energy in various forms, ranging from light, mechanical change, temperature difference, to variation of electromagnetic field, etc. Table 1 and Fig. 1 summarize and compares the five most essential technologies for ambient energy harvesting. Since we focus on the specific application area for self-powered flexible microsystems, only flexible or wearable configurations of the above five technologies are emphasized.

The fundamental rule of photovoltaic effect is that electrons overcome the potential barrier and are excited to a higher-energy state through absorption of lights. The light has to be over a certain frequency to possess sufficient energy to overcome the potential barrier for excitation, whereby the separation of charges results in the establishment of an electric potential [29]. Solar cells are prominent examples exploiting the photovoltaic effect. Up to date, solar cells can be classified into five main categories, including multi-junction cells, single-junction GaAs, crystalline silicon cells, thin-film technologies, and emerging others [30]. The first three types show better performance with the energy-conversion efficiency (*ECE*) ranging from 21.2% to 46%, and silicon-based solar cells are dominant in the commercial

Table 1
Comparison of five promising technologies for ambient energy harvesting. Since the specific application area is limited for self-powered flexible microsystems, only flexible or wearable configurations are emphasized. (up to the date of October, 2017).

Type	Schematic view	Voltage (V)[a]	Current (μA)[a]	Power density (mW/cm^2)[a]	Efficiency (%)[a]	Pros *vs* Cons
Photovoltaic Effect (PV)		0.5–0.9	100–500	5–30	0.3–46	High output power, continuous DC output, good basis of industrial fabrication For flexible organic solar cell, the conversion efficiency is still very low, only work under light
Thermoelectric Effect (ThE)		0.1–1	5–30	0.01–3	0.1–25	Sustainably working as a DC power source, easy to scale down, no moving component Low conversion efficiency, low output performance, large temperature difference
Electromagnetic Effect (EM)		0.1–10	N/A	N/A	5–90	High conversion efficiency, high current with low voltage, resistive impedance For wireless power transmission: short range, working at certain frequency; For magnet moving: heavy weight and big size, complexity
Piezoelectric Effect (PE)		1–200	0.01–10	0.001–30	0.01–21	Highly sensitive to external excitation, easily integrate and miniaturize in micro-nano scale Low conversion efficiency, low output performance, pulse output, high impedance
Triboelectric Effect (TrE)		3–1500	10–2000	0.1–100	10–85	High output power and energy conversion efficiency, no materials limitation, cost-efficient and remarkable flexibility Pulse output, high impedance, Friction damage

[a] These numbers are approximate values, in some cases they are estimated values based on the reported key characterization parameters.

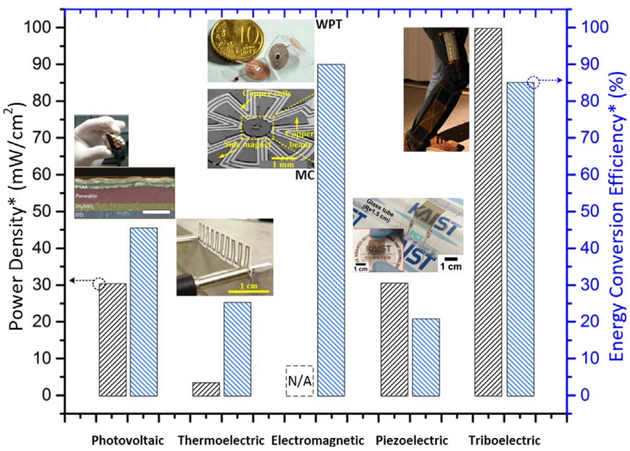


Fig. 1. Summary of technical progress of five promising technologies for ambient energy harvesting. The flexible and wearable configurations are emphasized as considering the specific applications for self-powered flexible microsystems. Thin-film solar cells, such as CIGS and perovskite cells, experienced a rapid development in recent years. Although only a half maximum value of energy conversion efficiency (*ECE*) is achieved (i.e., 23.3%) by these flexible solar cells compared with silicon-based solar cells, they show good flexibilities [30,144]. As the energy input, the light is a mandatory condition for the working of solar cells. Thermoelectric generators can be used to harvest the energy from thermal dissipation [145]. Its *ECE* is tightly related to the most important evaluation index of thermoelectric materials, i.e. *ZT*, and the temperature difference. The small temperature difference in practical applications and the quite low *ZT* below 2.5 restrict their output performances. Electromagnetic energy harvesting has two mechanisms, i.e. magnet-coil (MC) energy harvesting [35] and wireless power transmission (WPT) [37], whose efficiencies could achieve up to close to 90%. However, the output power of flexible MC type is normally below the μW level. Although the output power of WPT type can achieve a large value as providing a sufficient input power, the power transmission distance is very short at the centimeter level with a critical restriction on the alignment angle. Both piezoelectric and triboelectric effects can be utilized to convert environmental mechanical energy to electricity [46,146]. The output electric signals produced by piezoelectric generators possess a perfect linear correlation with external inputs, which can be used to realize high-precise sensing devices. But, its power generation ability is not competitive. Triboelectric nanogenerators (TENGs) is an emerging technology developed in 2012. After the past five-year blooming development, TENGs show the outstanding performance with high power density and ECE, achieving more than 100 mW/cm^2 and 85%, respectively. Reproduced with permissions from Springer Nature (2015), Elsevier B.V. (2014, 2017), AIP Publishing (2016), and Wiley (2014). (*Approximate values, in some cases estimated values based on the reported key characterization parameters.).

market [30]. However, the fragile and rigid properties impede their applications in wearable microsystems. By contrast, the latter two show good flexibility by fabricating specific functional materials on polymeric substrates, but their *ECE*s are still at a relatively low level, and the highest values of 23.3%, 22.1% and 11.9% have achieved with CIGS, perovskite and dye-sensitized solar cells, respectively [30]. Regardless the type of solar cells, they can only provide electric power under illumination condition with excludes their use during nighttime or in dark areas.

As featured in the section of introduction, human body itself is an ideal energy source with thermal dissipation and physical movement [13,14], which is considered as an attractive solution to meet the power demand of wearable electronics. For the energy generated by the thermal dissipation of human body, the thermoelectric effect is employed to convert it to electricity. When a temperature difference is applied to thermoelectric devices, an electrical potential, which can drive the electrons flow in the circuit loop to generate the electricity, is to be established due to the Peltier-Seebeck effect [31]. Thermoelectric generators can be divided into two categories: inorganic and organic types. Inorganic thermoelectric generators are made of alloys and intermetallics based on elements like Bi, Te, Sb, Pb, etc., which are essentially non-biocompatible or even toxic [32]. Organic thermoelectric devices are manufactured by using conductive polymers (i.e. conjugated polymers and certain coordination polymers) and small molecules (i.e. charge transfer complexes and molecular semiconductors) [32]. The properties of lightweight and flexibility make organic thermoelectric generators very attractive over the last decade. However, there is still a long way to go to enhance the *ECE*, which stays at a relatively low level below 25%. The *ECE* of thermoelectric generator is defined as a function of figure-of-merit (*ZT*), average working temperature, and temperature difference between the hot and cold ends. Thus, compared with *ECE*, $ZT = S^2\sigma T/\kappa$ is more essential to characterize the performance of thermoelectric generator, where S is Seebeck coefficient or thermopower, σ is electrical conductivity, κ is thermal conductivity and T is absolute temperature [33].

As for bio-mechanical energy harvesting, there are three main approaches: electromagnetic, piezoelectric and triboelectric effects. The electromagnetic effect is based on Faraday's law of electromagnetic induction back to 1831, which reveals the phenomenon that the voltage induced in a closed loop is proportional to the change rate of the magnetic flux through the loop area. This is the working principle of traditional magnetic generator, which constitutes the basic stones of modern society with electricity. The *ECE* of magnetic generator can achieve up to 90% with desirable output power. However, when we consider it for wearable applications, this traditional electromagnetic generator is obviously not suitable due to the heavy weight and large scale. Microscale electromagnetic generators were developed by employing microfabrication technology to miniaturize the device, and to also partially realize its flexibility by means of flexible coils [34–36]. Existence of hard magnet, however, makes it impossible to create fully flexible electromagnetic microgenerators. A further attractive alternative of electromagnetic induction is wireless power transfer (WPT), which can be utilized to deliver electrical power among multiple points with no need for a physical connection [17,37]. This method endows the maximum freedom to the powered electronics and has been demonstrated as a wireless power source in both laboratory and industry. The limitations of power transmission direction and short-range distance still challenge the further applications, although relay coils have been developed to remedy these obstacles [38].

Piezoelectric generator is another important approach to harvest the biomechanical energy, which has already been demonstrated to be a clean energy source and the self-powered active sensor [18,39,40]. The underlying mechanism of piezoelectric generators is the establishment of an electrical potential at the ends of piezoelectric materials under the external pressure, which is a reversible process [18]. Several kinds of materials are known to possess the piezoelectric property, including specific crystals, ceramics, polymers, and biological matter [18]. Piezoelectric materials can be divided into two main classifications, i.e. inorganic and organic materials. The most famous inorganic materials are piezoelectric crystals and ceramics, such as lead zirconate titanate (PZT), Barium titanate ($BaTiO_3$), zinc oxide (ZnO), and quartz [41]. The representative organic materials are polyvinylidene fluoride (PVDF) and its co-polymers, which are flexible and suitable for integration with wearable electronics. In order to have the piezoelectric property, a post process of polarization by applying ultra-strong electric field is necessary, which requires specific equipment and extra fabrication processes. Piezoelectric coefficient, also named piezoelectric constant, is one of the fundamental parameters to quantify the piezoelectric characterization of materials, which can vary in a wide range. Thus, the performance of piezoelectric generator is directly related with the piezoelectric characterization of selected material, whose selection range is actually limited. The outstanding linear feature between input pressure stimulation and output electric signal makes piezoelectric generators suitable to serve as self-powered transducers [42]. It is worth mentioning that piezoelectric nanogenerators (PENG) based on ZnO nanowires experienced an intense development phase in the past ten years [43]. These PENGs show attractive potentials in many fields covering not only energy harvesting but also sensing. However, as a power source, the output performance is not competitive.

The phenomenon of charges generated at the friction interface of two different materials (i.e., triboelectric pair) is defined as electrification effect. Although the observation and description of electrification effect date back to more than three thousand years ago, routes to efficiently accumulate charges, generate the electricity and minimize the size are still subjects of research. In 2012, a new ambient energy harvesting technology named triboelectric nanogenerator (TENG) was developed based on the coupling of electrification effect and electrostatic induction [19]. By placing two electrodes on the backside surfaces of triboelectric pair, electrification effect and electrostatic induction are combined together for effective power conversion [44,45]. In the past five years, TENGs have attracted lots of attentions due to their excellent properties of high-output performance, low cost, maintenance free, and sustainability. Several techniques have been developed to strengthen and extend the capabilities of TENGs, and the power density has achieved up at tens mW/cm^2 level [25]. Furthermore, the maximum power conversion efficiency reached 85% [46]. Since electrification effect occurs between almost all materials as long as they have different compositions or surface morphologies/strains, thus this technique is tolerant with material selection, and plenty of polymers and organic materials can be employed to realize flexible and even stretchable devices [47]. In addition, micro/nano patterned surfaces are commonly utilized to maximize the effective friction area and enhance the output performance [48–52]. From the above analysis and comparison, we can see that TENGs show much more attractive potentials and are considered as one of the most promising alternative approaches. In the following of this review, we summarize the emerging technology of TENG serving as the key component of self-powered flexible and wearable microsystems, including the innovation of working principle and material selection, the functionalization of sensing and actuating, and the future tendency of all-in-one concepts.

3. Progress of triboelectric nanogenerators

TENGs can be categorized into four main types according to different operating principles, including contact-separation (CS) mode, relative-sliding (RS) mode, single-electrode (SE) mode and free-standing (FS) mode, as shown in Fig. 2. CS mode is the first prototype of TENG, which consists of a triboelectric pair made of two different materials and two electrodes placed in the backside [53–59]. The working principle of CS-mode TENG can be described as follows. Firstly, the whole TENG is electrically neutral and the triboelectric pair are separated. Under the external force, two materials contact with each other to generate surface charges at the friction interface. Due to the different abilities of losing or capturing electrons during electrification, one material of the triboelectric pair loses electrons and shows positive potential, while the other captures electrons and shows negative potential. In principle, the charge amounts on the surface of triboelectric pair are equal. Secondly, when the external force is removed, the triboelectric pair separate and an internal potential is established. During the separation process, this internal potential will induce charges flow from one electrode to the other through the connection loop to balance the change of electrical potential due to electrostatic induction. Such process can generate a positive current. This is named the process of separating. Thirdly, when the external force is applied to the TENG again, the triboelectric pair move towards each other, which will induce charges to flow back creating the opposite change of electrical potential. Thus, a negative current is formed, and this process is named approaching. Finally, the triboelectric pair contact again to start a new cycle. Therefore, when TENG repeats these separating-approaching cycles, a periodical electric output is generated with positive and negative parts. More details appear in Fig. S1 in the Supporting information file. The other four types of TENGs are all based on the combination of electrification effect and electrostatic induction.

In the beginning, the output performances of CS-mode TENGs were not so competitive and still kept at a low level of several or tens volts. Later, increasing surface roughness and specific geometry designs for rapid separation were introduced to significantly enlarge the output voltages and power densities of CS-mode TENGs up to hundreds volts and tens of mW/cm^2 [51,53]. The underlying mechanism of output enhancement by increasing surface roughness is maximizing the effect friction area to generate more surface charges [45]. As for the arch-shaped optimization, a capacitance equivalent mode can be used to roughly describe the basic rule of output enhancement [60]. Assuming the surface charges (Q) are constant, when the capacitance (C)

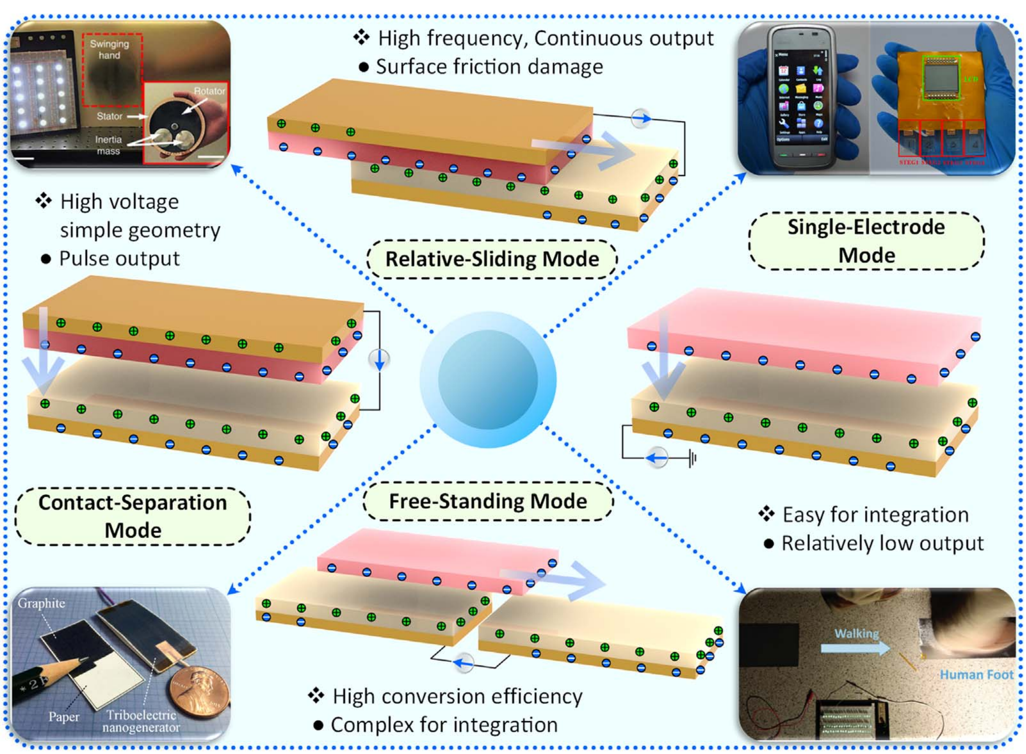


Fig. 2. The summary of triboelectric nanogenerators (TENGs). According to the operation mechanism, TENGs is classified to four types, including contact-separation (CS) mode, relative-sliding (RS) mode, single-electrode (SE) mode and free-standing (FS) mode. In principle, all types of TENG scavenge the ambient mechanical energy based on the combination of triboelectrification effect and electrostatic induction. The CS TENGs can generate high-voltage pulse output with simple geometries [101,147–152]. The RS TENGs show an attractive property of generating continuous electricity at high frequency, although the surface friction damage is a big challenge [66,153–157]. The SE TENGs are constructed with only one triboelectric surface while using human skin as the other, and this simplified geometry makes it easy to be integrated with other electronics [75,158–162]. However, the output electricity is also relatively low. The FS TENGs with two fixed electrodes show the remarkable energy conversion efficiency [70,163–167].

Table 2
The develop roadmap of the configuration of triboelectric pairs (up to the date of October, 2017). The date in the form represents the first time of this triboelectric pair reported in publications. The materials in left and the right columns mean the positive and the negative parts in each triboelectric pair, respectively.

Triboelectric Pairs		PTFE	PDMS	Polyimide	FEP	Parylene	PVC	Rubber	PFA	Graphene	Epoxy	Polyolefin	PVDF	Polyester	Ground	PE	Polyamide	PU	PET	Alginate Sodium	Human Skin	Silicone	PP
Metal	Al	2013.04	2012.11	2013.05	2013.09	2016.03	2014.03	2015.05	2013.01			2014.02	2014.06					2015.09					2017.03
	Ag	2012.12	2013.08																				
	Au		2013.04	2014.11	2017.04						2013.09												
	Cu	2013.06	2013.08	2014.03	2015.06		2015.08										2015.03						
	Ni		2016.08	2016.01		2015.03																	
	Steel	2014.03			2015.01																		
Oxide	ITO	2016.08	2013.02																				
	TiO_2	2013.04	2014.01																				
	Al_2O_3									2015.01													
	SiO_2	2014.05	2013.07	2014.04		2013.11																	
	Graphen Oxide																				2017.01		
Polymer	PET	2013.06	2012.05	2012.01			2016.06																
	PMMA			2012.08																			
	Nylon	2013.04		2015.11										2014.07									
	PU	2015.05																					
	PPy	2015.12																					
	Urethane																					2017.01	
	PVA																			2016.11			
	EVA														2014.12								
	Biodegradable Polymer			2016.03																			
Others	Latex				2014.07				2013.12														
	Carbon Black							2016.06															
	CNT	2014.04																					
	Cellulose				2016.09																		
	Silk fibroin			2016.01															2015.12				
	Paper	2017.01																					
	Human Skin		2013.08		2014.05			2016.09															
	Liquid	2014.05	2013.01	2015.01	2014.04					2016.07						2015.02							
Total pairs		14	11		8	3			2		1												

EVA: ethylene-vinylacetate [168], PP: polypropylene [169], PPy: polypyrrole [170], PU: polyurethane [171], FEP: fluorinated ethylenepropylene [172], PFA: polyfl uoroalkoxy [173], PVC: polyvinyl chloride [174], ITO: indium tin oxide [175], CNT: carbon nanotubes [176], PVDF: polyvinylidene fluoride [177], PDMS: poly(dimethylsiloxane) [178], PMMA: poly(methyl methacrylate) [179], PE: polyethylene [180], PET: polyethylene terephthalate [181], Biodegradable polymer [182]: poly(L-lactide-co-glycolide) (PLGA), poly(3-hydroxybutyricacid-co-3-hydroxyvaleric acid) (PHB/V), poly(caprolactone) (PCL), poly(vinyl alcohol) (PVA).

decreases sharply due to the stronger mechanical restoring force from the arch-shaped design, the potential difference ($U = Q/C$) between two electrodes increases sharply. The advantages of CS-mode TENGs are clear that the output voltage is high, while the simple geometry make it easy to be used to convert most mechanical energies, such as pressing, impacting, bending, shaking, vibration, etc. However, it is hard to use it for harvesting mechanically rotational energy, as the frequency effect should be considered for optimized designs [45].

The relative-sliding (RS) mode TENGs were developed in April, 2013 [61,62]. Further optimization allows such RS-mode TENGs to harvest the rotational energy as well as air-flow energies [63–69]. The most attractive benefit of RS-mode TENG is its ability for high-frequency applications and the continuous output electricity. However, this unique operation method of relatively sliding also brings a critical challenge of friction damage to the surfaces of triboelectric pair. Although several research works have reported the considerable reliability of RS-mode TENGs, the long-term stability in practical applications is still a key concern. Later, a free-standing TENG was proposed in January 2014, which has a similar operating principle to that of RS-mode TENG but the two electrodes are fixed without motion [70,71]. Theoretically, the energy conversion efficiency of FS-mode TENG can achieve up to 100%. But the free-standing design of movable triboelectric layer make it not easy to be integrated with other electronic devices and systems. The forth type of TENG is named single-electrode (SE) mode [72–74], and in some cases it is also named single-friction (SF) mode [75–77]. The motivation of SE/SF-mode invention is to further simplify the configuration of TENG by removing one of triboelectric pair (SF mode) or electrodes (SE mode). Compared with other prototypes made of two triboelectric layers (i.e., triboelectric pair), SE/SF-mode TENGs only consist of one triboelectric layer by employing human skins or other existing objects as the other triboelectric material to form a triboelectric pair. The sole electrode is connected to ground electrode through a load, and a periodical current will be generated between them when a relative motion of triboelectric pair occurs cyclically. SE/SF-mode TENGs are powerful for portable electronics integration, and one of the most promising potentials is to be integrated with electronic screens to harvest the biological mechanical energy from sliding, typing, touching screens in daily use [73,75].

It is worth mentioning that there are also several other constructions, including liquid-metal TENGs [78,79], textile TENGs [80–86] and so on, but their working principles are still based on one of the above four prototypes. For examples, liquid metal provides a sufficient omnidirectional friction while the side effect of energy loss is minimized, which directs an energy conversion efficiency of 70.6% up to date [78]. Textile-based TENGs showed outstanding features of flexibility and stretchability since fibers and fabrics are employed as key components [87–89]. As an attractive future vision, people can wear the clothes fully or partially made of textile-based TENGs to convert body motion energy to electricity for powering wearable electronics.

Besides the above tendency, another valuable summary of TENG's development is the progress of materials. As figured out in the description of TENG's working principle, the core of electrification is the different capabilities of losing or capturing electrons between the triboelectric pair. In principle, if the ability relative difference of triboelectric pair is larger, then the output performance of fabricated TENG is better due to the enhancement of generated surface charge density. A table of triboelectric series was established, which qualitatively pints out these ability difference, as shown in Table S1 in Supporting information file. In the past five years, many different triboelectric pairs were studied as material candidates to construct TENGs, as summarized in Table 2. In this table, the materials in the left column highlighted in yellow color represent that they are easy to lose electrons and show positive potential. By contrast, the materials in the top row highlighted in blue color represent that they are relatively easy to capture electrons and show negative potential.

According to Table 2, the most widely used materials are Polytetrafluoroethylene (PTFE), Polydimethylsiloxane (PDMS), Polyimide (PI) and Fluorinated ethylene propylene (FEP), which composes 14, 11, 11 and 8 triboelectric pairs, respectively. For example, according to the publications, PTFE can be used to construct triboelectric pairs with other 14 different materials. The main reason is attributed to their remarkable abilities of capturing electrons during electrification effect, since they occupy the bottom-tier levels in triboelectric series. The sequence of electron capturing ability is listed as PTFE > PDMS > PI [20], and FEP is highly similar to PTFE with tiny difference in molecular structure. PTFE, also known as Teflon, has the strongest ability to lose electrons among all the known materials and shows ultra-stable chemical and physical properties. PDMS is a bio-compatible material which is very easy to be micro/nano patterned by using molding cast process, and it also keeps a good stretchable capability. PI, also known as Kapton, can be prepared as elastic thin films and enable to work under high-temperature conditions up to 260 °C. As for the negative part of triboelectric pair, materials can be divided into four groups, including metal, oxide, polymer and others. Metals can serve as both triboelectric material and electrode simultaneously [90–92], which further simplifies the construction of TENG. Oxide compounds, including Indium tin oxide (ITO), TiO_2, Al_2O_3, SiO_2 and graphene oxide, are widely used. Among them, ITO shows a unique feature of conductivity and an outstanding property of transparency. Polymers are the most important type of triboelectric materials, and thus, TENG is also named organic nanogenerator, which is the first mechanical energy harvesting technique using organic materials [20].

One of the most attractive benefits of TENG is its tolerance to material selection, since electrification effect exists between almost all two different materials. Therefore, as shown in Table 2, there are a great many triboelectric pairs made of different materials. However, the ability difference of losing or capturing electrons determines the electrical performance of fabricated TENG. Thus, in this view point, the materials are expected to possess the outstanding electrical property of easily losing or capturing electrons. Exploring novel triboelectric materials is one of the most significant research topics. Moreover, in order to meet the requirement of constructing flexible and wearable self-powered microsystems, triboelectric materials are expected to show excellent flexibility or even stretchability, environment-friendly or even bio-compatible features. In brief, the polymeric materials possess remarkable flexible and stretchable capabilities, like PDMS, rubber, epoxy, PU, etc. The key issue to realize stretchable TENG is the manufacture of stretchable electrodes, which normally are fabricated by mixing conductive nanowires, such as carbon nanotubes (CNT) and silver nanowires, with polymeric materials.

4. TENG featured developments for self-powered microsystems

In this section, the development tendency of TENGs focusing on self-powered microsystems is summarized by featuring several published work. It contains three parts: new materials, active sensors and powering actuators.

4.1. New materials

There are two clear trends of materials observed recently. Firstly, fibers and fabrics were identified as suitable materials for wearable TENGs, as shown in Fig. 3(a)–(c). Secondly, the feasibility of using eco-friendly and biocompatible materials were widely investigated, as shown in Fig. 3(d)–(f).

TENGs made of fibers or fabrics show remarkable soft features and can be easily integrated with cloths or even serve as clothes directly. Here, three published work are selected to explain more details of fabric-based TENGs. In January 2017, a self-powered wireless smart patch was reported by M. Shi et al. from Peking University [89], as shown in Fig. 3(a). In this work, a thin film of CNT/cotton fabric was attached to the surface of cloth and faced the other movable cloth to compose a fabric-based TENG. When people wearing this TENG are working or running, the periodical separation of CNT/cotton-Cloth triboelectric pair will generate the electricity. In addition, a conductive PDMS film mixed with Ag nanowires was placed in the backside of CNT/cotton film with a certain distance, which serves as a wireless receiver to sense the relative motion of fabricated TENG based on electrostatic induction. This self-powered wireless smart patch showed a good transmission capability with 26.6% efficiency while the distance was 1 cm. Another fabric-based TENG was developed by Pu et al., which employed a fabrication method of textile to weave TENGs, as shown in Fig. 3(b) [83]. A conductive fabric was firstly prepared by coating a thin layer of Nickel on the surfaces of polyester cloth, and subsequently a thin layer of Parylene was coated. Thus, Nickel fabrics and Parylene fabrics composed the triboelectric pair and were weaved together to form clothes. The maximum peak value of output power density of fabricated TENGs achieved to 393.7 mW/m^2 with an external load of 70 MΩ. The third type of fabric-based TENGs was reported by Kim et al. [84] Each fiber itself is a TENG made of an inner Al wire coated by Au and an external PDMS tube, as shown in Fig. 3(c). The surfaces of triboelectric pair (i.e., PDMS and Au) were nanostructured to increase the effective friction area. These fabricated TENG fibers were weaved as clothes to harvest the biological mechanical energy. The electric output of this TENG was attractive with voltage, current and instantaneous power of 40 V, 210 μA and 4 mW, respectively. In addition, it exhibited high robustness behavior even after 25% stretching. In summary, this textile weaving process provides a large-scale high-throughput technique to produce wearable TENGs, which attracted much attention in the past three years. Several relevant work were also reported by Kim, et al. [82], Hong [93], Chou and Xue [94], Andrew [95], Peng [96], Hu and Zheng [97], Kim [98], and so on.

Although TENG is considered as a green power source without pollution production, conventional materials of TENGs may bring side effects to the environment, such as heavy metal pollution of soil and white pollution of plastic. Therefore, a new trend of TENG development is the study on the possibility of introducing eco-friendly materials, and the target is minimizing negative effects from TENG materials. Among these eco-friendly materials, biodegradable materials attracted much attentions and had a rapid growth in the past two years. In 2016, TENGs based on cellulose nanofibrils (CNFs) were reported by Yao et al. [99], as shown in Fig. 3(d). These biodegradable CNFs were proved to be a good candidate of triboelectric positive materials, and furthermore, the authors studied the integration of fabricated CNF-TENGs with a fiberboard made of recycled cardboard fibers using a chemical-free cold pressing method. The presented device showed a good electrical output performance with voltage and current of 30 V and 90 μA, respectively. Additionally, Zhang et al. demonstrated two interesting biodegradable materials, i.e. silk fibroin and common paper, as promising candidates of triboelectric positive materials [100,101]. Silk fibroin is an emerging biodegradable natural material with the controllable water solubility, and furthermore, it occupies a top-tier position in the triboelectric series and possesses the outstanding ability of losing electrons easily during electrification, which is significant to enhance the power density of TENG. Compared with conventional materials such as PET, PI, Teflon and PDMS, using silk fibroin enlarges the output voltage of TENG manifold up to nearly one order of magnitude in the best case. In addition, silk fibroin film has the advantageous property of 90% transmittance in the visible light spectral region to enables the realization of an ultra-transparent device, as shown in Fig. 3(e). Fig. 3(f) shows shape memory polymers (SMPs) for body motion energy harvesting and self-powered mechanosensing. The SMP was prepared by incorporating a semicrystalline thermoplastic polymer (polycaprolactone, PCL) in a chemically cross-linked elastomer (acrylate), forming a semiinterpenetrating polymer network (semi-IPN). By using this polymeric material program technique, shape memory polymers were successfully realized and utilized for the first transformable smart energy harvester and self-powered mechanosensation sensor. There are also other advancements in TENG materials, as reported in Refs. [184–187]. These further improvements by exploring new inexpensive electrification materials [101], by programming advanced functional materials [184] and by simplifying the fabrication process [101,188] open a new chapter of

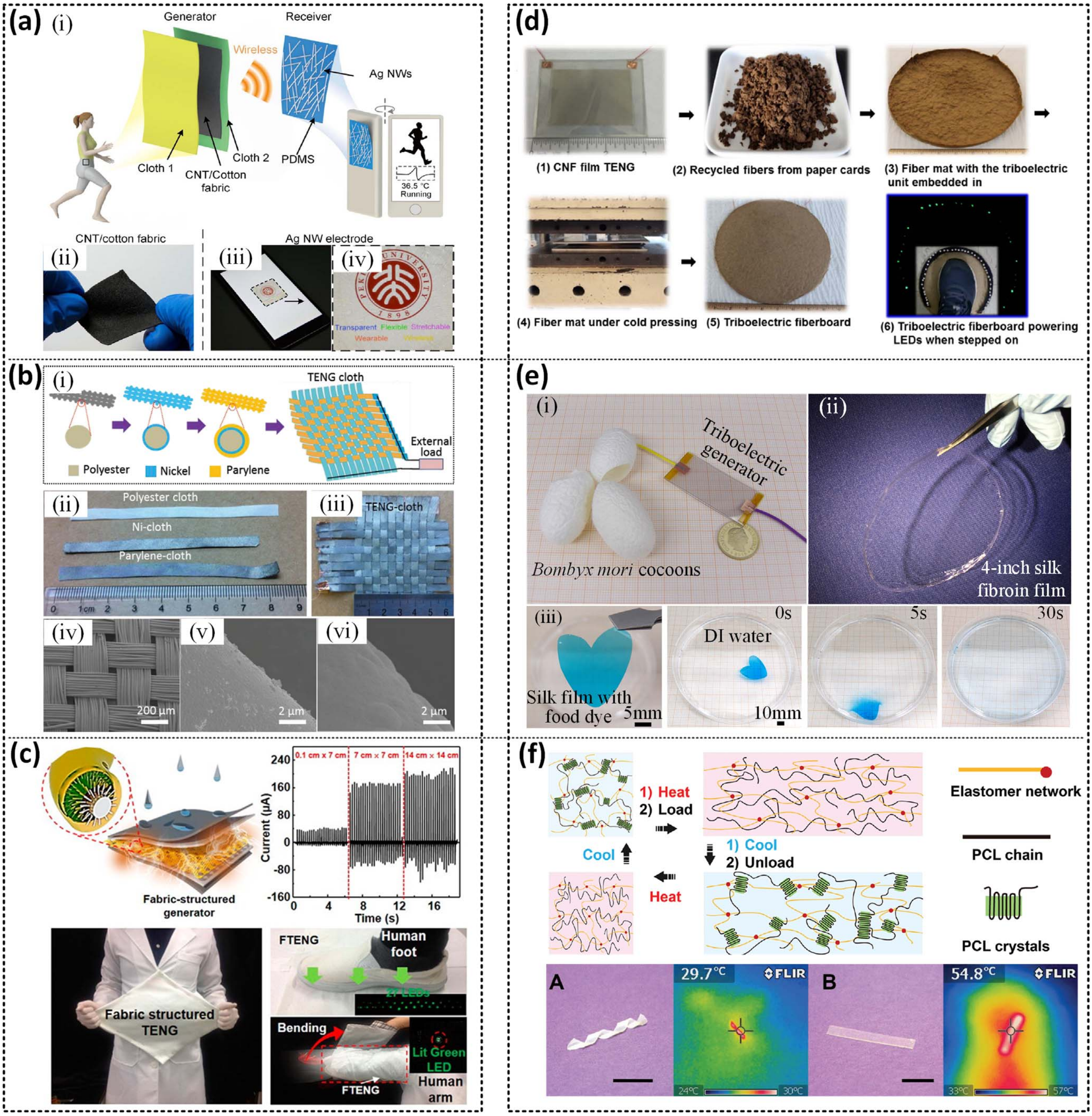


Fig. 3. Progress of new materials developed for flexible and wearable triboelectric nanogenerators (TENG), including (a–c) fiber/fabric-based materials and (d–f) eco-friendly and biodegradable materials. (a) Self-powered fabric-based smart patch for healthcare monitoring. Reproduced with permission from Elsevier B.V. (2017) [89]. (b) Cloth-based TENG for powering wearable electronics. Reproduced with permission from Wiley (2015) [83]. (c) Highly stretchable 2D fabrics for wearable TENG under harsh environments. Reproduced with permission from ACS (2015) [84]. (d) TENGs and power-boards fabricated by using cellulose nanofibrils and recycled materials. Reproduced with permission from Elsevier B.V. (2016) [99]. (e) Natural biodegradable materials of silk fibroin was introduced to construct TENGs, respectively. Reproduced with permissions from Elsevier B.V. (2016) [100]. (f) A shape memory polymer made of acrylate and semicrystalline polycaprolactone (PCL) was demonstrated to be TENGs for body motion energy harvesting and self-powered mechanosensing. Reproduced with permission from Wiley (2018) [183].

TENG to bring a real impact to life applications.

4.2. Active sensors

In the section of introduction, the concept of self-powered flexible and wearable microsystems was briefly described. In principle, as the key component, TENGs serve as power sources to supply the function of these microsystems, which consist of two main parts, i.e. sensing and responding. In the above sections, the powering capability of TENG has been concluded, thus the functionalization of TENG for sensing and actuating are to be summarized in the following two sub-sections.

One of the most attractive benefits from TENGs is the quantitative relation between external physical inputs and electrical outputs, which enables TENGs to monitor the environmental changes in real time. Thus, TENGs can be utilized as both power sources and sensors simultaneously, which are also named active sensors. Many different types of TENG-based active sensors have been demonstrated for detections of pressure [102–109], strain [110–113], gesture and motion

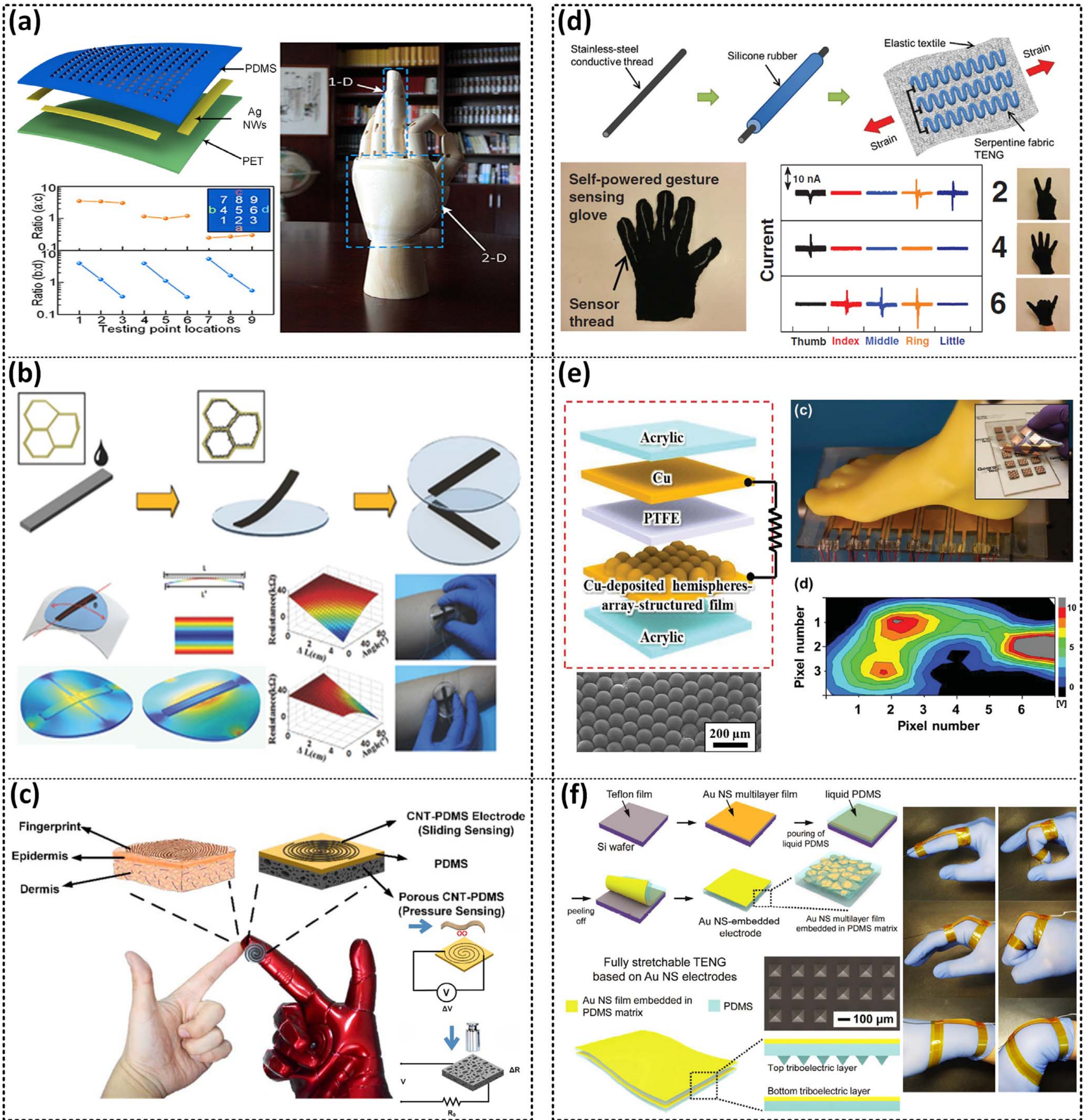


Fig. 4. Progress of flexible and wearable triboelectric nanogenerators (TENGs) serving as active sensors by using the quantitative relation between TENG's output and external variable factor. (a–c) The group at Peking University led by Zhang reported three types of self-powered TENG, which can be used to detect or monitor the pressure and position, the tension and direction, and the environmental humidity, respectively. Reproduced with permissions from ACS (2016), Wiley (2016) and Elsevier B.V. (2014) [102,104,122]. (d, e) The group at Georgia Institute of Technology led by Wang reported two self-powered sensors based on TENG for body motion identification and multiple-point pressure detection. Reproduced with permissions from Wiley (2017) and (2016), respectively [123,124]. (f) Kim, Lee et al., reported fully stretchable and highly durable triboelectric nanogenerators for self-powered human-motion detection. Reproduced with a permission from Elsevier B.V. (2017) [117].

[114–119], humidity [120,121], etc. Here, six typical TENG-based sensors are selected and summarized in Fig. 4 to give more details. Three work published by Zhang et al. at Peking University are shown in Fig. 4(a)–(c). Fig. 4(a) shows self-powered flexible analogue smart skin based on TENG, which can be used to detect contact position and velocity of the target [104]. The device was composed of a surface-textured PDMS square film placed onto a PET foil and four strip electrodes (Ag nanowires) placed along four rims. The operation mechanism is the combination of single-electrode contact electrification effect and planar electrostatic induction. Taking fingers as example, when fingers touch the PDMS surface, triboelectric charges will be generated at the friction interface due to electrification effect. Subsequently, when fingers leave PDMS surfaces, charges will be induced in electrodes resulting from planar electrostatic induction. According to relative potential differences of four electrodes, the touch position and moving speed of fingers can be monitored. The sensitivity of fabricated TENG-based smart skin is outstanding with a resolution of 1.9 mm with only four terminals. In 2016, a stretchable sensor made of CNT-PU (carbon nanotubepolyurethane) sponge was developed [102], which can be used to realize sensing purposes of omnidirectional bending and pressure independently, as shown in Fig. 4(b). The messages of both direction and curvature of bending behavior can be given simultaneously, which is attributed to the interaction of two CNT-PU sponge strips placed orthogonally. More importantly, this work employed triboelectric mechanism to distinguish behaviors of pressing and bending, which makes it very useful in several specific applications, such as complex multi-directional bending and soft substrate irregular deformation. Recently, a fingertip-inspired electronic skin based on the combination of sliding triboelectricity and piezo-resistivity was reported, as shown in Fig. 4(c) [122]. The as-presented device can detect the moving object in both vertical and horizontal directions at the same time, owing to piezo-resistivity of porous carbon nanotube-polydimethylsiloxane (CNT-PDMS) substrate and electrification effect between targets and double spiral CNT-PDMS electrodes, respectively.

In 2016, single-thread-based wearable TENGs and their application in cloth-based self-powered human-interactive and biomedical sensing were reported by Wang et al., as shown in Fig. 4(d) [123]. In this work, TENG based on single-thread design was proposed, where a stainless-steel conductive thread and its external covering layer of silicone rubber formed the triboelectric pair. The fabricated TENGs were integrated with an elastic textile, which showed an outstanding strain ability of about 100%. This textile-based design make it possible to extract mechanical energy when contact and friction with skin or other clothes, and more importantly, to realize gesture sensing, human-interactive interfaces, and even human physiological signal detection. For multiple-point detection, the typical prototype of using TENG as active sensor is the design of TENG arrays. A fully packaged self-powered triboelectric pressure sensor employing hemispheres array was reported in 2016 by Kim, Wang, et al., as shown in Fig. 4(e) [124]. This work presented a TENG composed by the triboelectric pair of PTFE film and Cu-deposited hemispheres-array-structured PDMS film. The unique design of hemispheres array is advantageous for surface roughness increase, high mechanical durability and high elastic property. Furthermore, an active self-powered sensing array by using the fabricated TENGs was demonstrated to map the pressure distribution of object placed on it. Fig. 4(f) shows fully stretchable and highly durable triboelectric nanogenerators for self-powered human-motion detection reported by Kim, Lim et al. [117] In this work, a fully stretchable and durable TENG with Au nanosheets embedded into both PDMS matrix and micro-patterned PDMS was developed. It was proven that this method can be used to significantly improve the mechanical flexibility and stretchability. The authors demonstrated that the fabricated devices can be used to detect the human body motion as an active sensor by mounting the fabricated TENG on index finger, knuckle and wrist. Resulting from different types of body physical motions, corresponding electrical signals are generated by the TENG.

4.3. Driving actuators

Sensing and monitoring changes of ambient factors are the first task for self-powered microsystems, and further, the more important function is to respond these changes. Thus, demonstrating feasibilities of driving actuators as required by using TENG is essential. Several micro actuators have been successfully driven by using the instantaneous electrical signals generated by TENG, resulting from its unique feature of ultra-high voltage at the levels of hundreds or even over one thousand volts. Six typical applications of driving actuators by using TENG are summarized as shown in Fig. 5. In 2013, Zhang et al. reported a demonstration of successfully stimulating the frog's sciatic nerve to control the movement of its leg through placing a neural prosthesis connected to the fabricated TENG, as shown in Fig. 5(a) [120]. When applying a compressive force to the TENG by fingers, an electrical pulse was generated and applied to the neural prosthesis via the connecting wires. The neural prosthesis consists of implantable microneedle electrode array, which is to generate a uniform electrical field when the instantaneous electrical output of TENG is applied to it. Thus, the sciatic nerve of frog was stimulated and control the motion of frog's leg muscle. This work of driving an implantable 3-D microelectrode array without any energy storage unit or rectification circuit revealed an attractive future version of self-powered neural prosthesis, which opens a new chapter of TENG applications for driving biomedical microsystems. In 2017, Li et al. reported a new application of TENG for sensitive nanocoulomb molecular mass spectrometry, as shown in Fig. 5(b) [125]. In this work, the authors realized a quantitative control of total ionization charges in mass spectrometry by adjusting the output of TENG. High voltage produced by TENG is the key point to produce single- or alternating-polarity ion pulses and induce nanoelectrospray ionization (nanoESI) and plasma discharge ionization. Precisely controlled ion pulses can be produced in the range of 1–5.5 nC with an onset 1.0 nC charge. The proposed system showed remarkable sensitivity with about 0.6 zeptomole, which was powerful for mass spectrometry analysis.

Among the applications of driving actuators by using TENG, one of most important fields is microfluidics. Fig. 5(c) and (d) show two latest progresses. Song et al., reported a self-powered implantable drug-delivery system, which is composed of a TENG-based energy harvester and an electrochemical microfluidic pump [126]. When the disk-shaped TENG works continuously, its electrical output is transformed and rectified to DC current and is applied to electrodes of the electrochemical microfluidic pump. Thus, oxygen and hydrogen gases are produced to pump liquid droplets (i.e., drug) out resulting from the electrolysis effect. Furthermore, the rotating speed of TENG can be utilized to control pumping flow rates changing in the range of 5.3–40 μL/min. In 2017, Zhang et al. reported a controllable manipulation of liquid droplets by using TENG [101]. A conductive needle connected to TENG was immersed into a liquid droplet, and the relative position between needle and droplet determines the sliding direction of liquid droplet after an electrical pulse was applied by pressing TENG. A reasonable explanation on the controllable mechanism was given by finite-element simulation, and it clearly showed that the electrical potential distribution was dissymmetrical, which meant the electrostatic force larger in the side closer to the needle. Based on this operation principle, it was easily to push two liquid droplets to move towards each other and eventually merged. This is the first demonstration of using TENG to realize the directional transportation of liquid droplet without any external circuit, which make TENG closer to the practical microfluidic applications.

Additionally, TENG also shows remarkable capability to drive movable micro-electro-mechanical systems (MEMS) actuators, which are the key components to construct the Internet of things (IoT). In 2016, a micro-cantilever was demonstrated to be driven by connecting directly to a fabricated TENG, as shown in Fig. 5(e) [100]. In one working cycle of TENG, two potential peaks were generated. Correspondingly, there were two potential differences generated between micro-cantilever and bottom electrode. And then, an electrostatic force was applied to the suspended micro-cantilever, and it was pushed to contact the bottom electrode twice. A theoretical analysis was also conducted to calculate the quantitative relation between electric output of the TENG and deformation of the micro-cantilever. Another demonstration of stimulating acrylic elastomers by TENG was also reported, as shown in Fig. 5(f) [127]. Dielectric elastomers have outstanding response features as artificial muscles, and are considered as typical actuator materials operated under high voltage. In this work, a thin film dielectric elastomer actuator (DEA) was successfully actuated by the instantaneous electrical output of a fabricated TENG. For instance, a 100 cm^2 TENG working stably with the velocity in the range of 0.1–10 cm/s can be used to induce a 14.5% expansion strain for DEA devices.

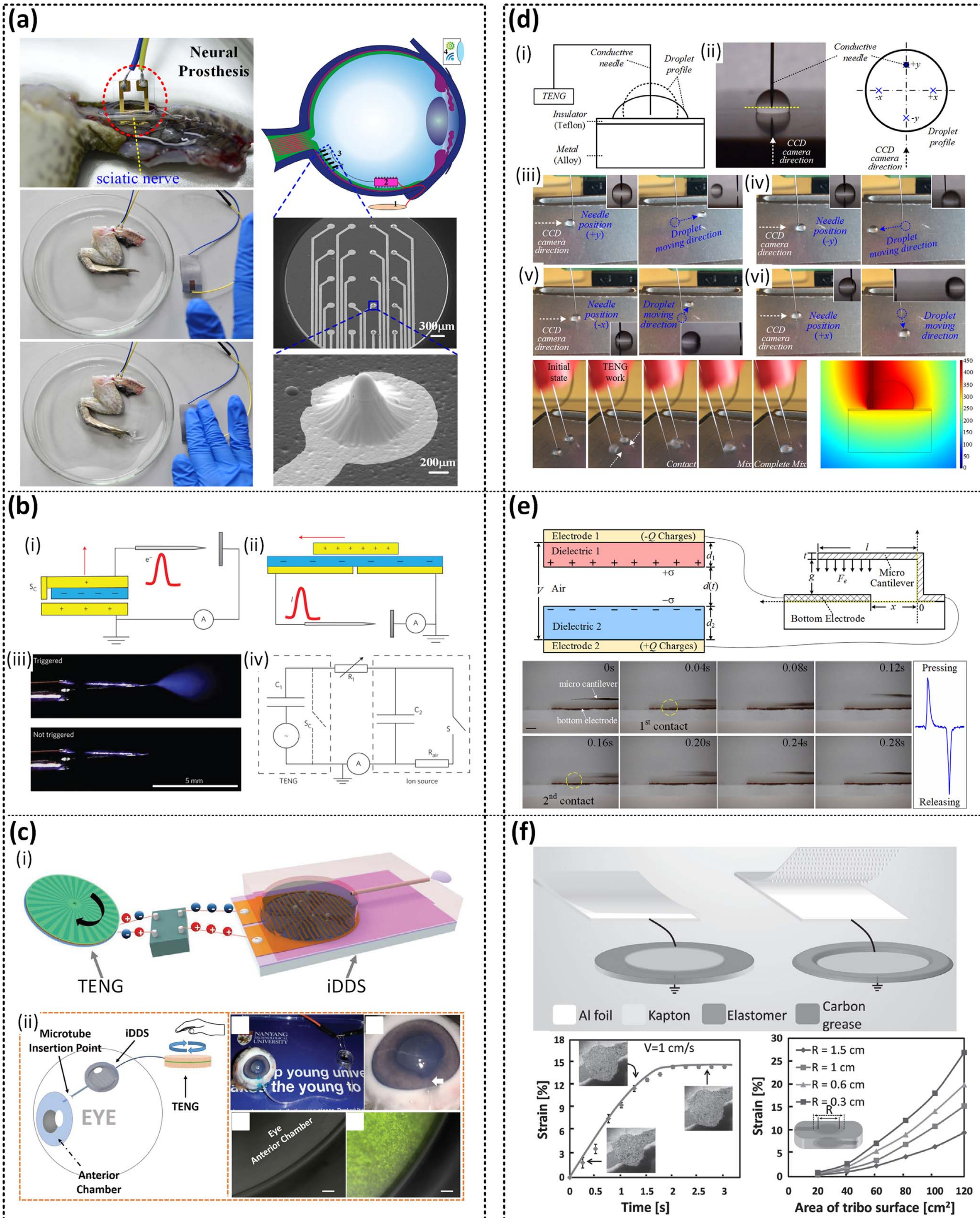


Fig. 5. Progress of flexible triboelectric nanogenerators (TENGs) driving actuators which is indispensable for realizing the self-powered functional microsystems. In the past five years, TENGs have been demonstrated to power and drive many types of actuators as demanded, including (a) neural prosthesis for nerve stimulation [120], (b) controller of ionization charges in mass spectrometry [125], (c) drug delivery [126], (d) controlled transportation of liquid droplet [101], (e) microcantilever [100] and (f) acrylic elastomers [127], etc. Reproduced with permissions from Elsevier B.V. (2013, 2016, 2017), Springer Nature (2017), and Wiley (2016, 2017).

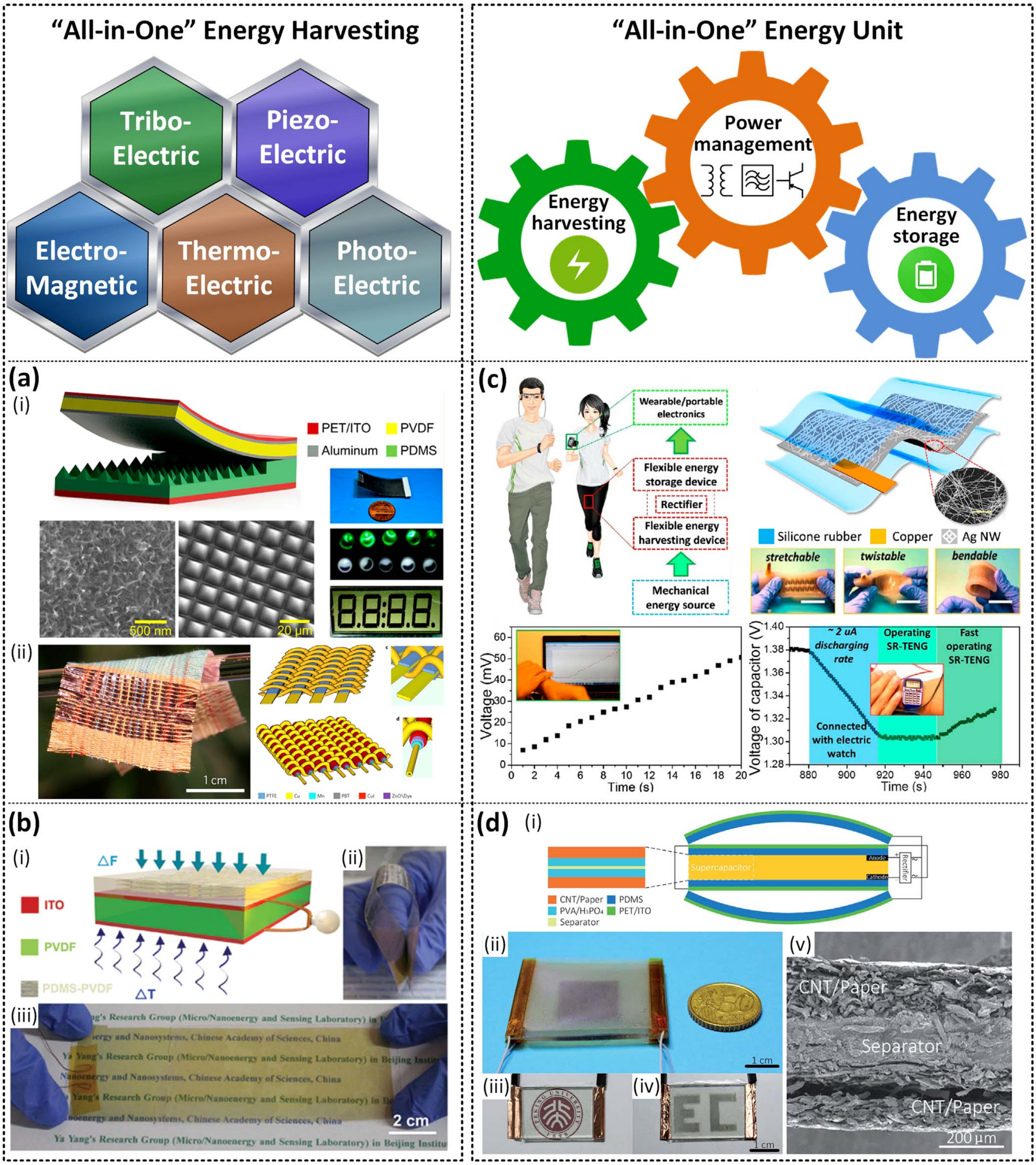


Fig. 6. Progress of "All-in-One" triboelectric nanogenerators (TENGs), which can be summarized as two classifications, including (left image) all-in-one energy harvesting and (right image) all-in-one energy unit. For all-in-one energy harvesting, two or more energy harvesting mechanisms are combined together to form hybrid energy harvester to enhance the energy conversion capability and enlarge the output power. (a-i) Piezoelectric-triboelectric hybrid [49], (a-ii) Photovoltaic-triboelectric hybrid [88], and (b) triboelectric-piezoelectric-pyroelectric hybrid [140]. For all-in-one energy unit, the concept is integrating energy harvesters, power module circuit and energy storage together to form a power unit that can be used directly to supply electricity for microsystems. (c) Shape-adaptive self-charging power package for wearable electronics [142], and (d) Integrated self-charging power unit with flexible supercapacitor and TENG [143]. Reproduced with permissions from ACS (2013, 2016), Springer Nature (2016), Wiley (2016), Elsevier B.V. (2014) and The Royal Society of Chemistry (2016).

4.4. "All-in-one" energy unit and energy harvesting

Besides the above development tendencies, recently there is an important concept of "all-in-one" energy unit reported frequently, in which TENGs are integrated with other circuits to form a direct-use power unit. In addition, a concept of "all-in-one" energy harvesting is proposed in this work, in which TENGs are integrated with other energy harvesting mechanisms to form hybrid energy harvesters. Fig. 6 shows

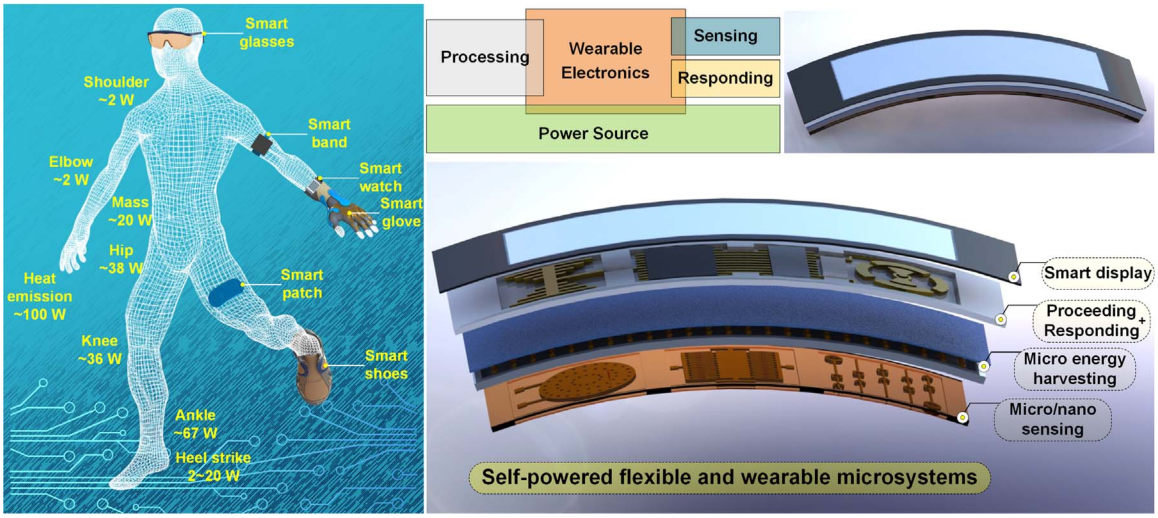


Fig. 7. Prospect: "All-in-One" self-powered microsystems. Human body is a movable and sustainable power source generating biological mechanical energy and thermal energy by physical movement and heat dissipation [13,14]. By using appropriate techniques, such as piezoelectricity, triboelectricity and thermoelectricity, these biological energy can be harvested and converted to the domain of electricity to power the portable electronics and microsystems. As an attractive future vision, herein a self-powered flexible and wearable microsystems without the need for battery or laying a long wire for frequently charging is proposed, which can be utilized to harvest the energy from the ambient to support the continuously and autonomously working of themselves.

these all-in-one concepts.

The idea of all-in-one energy harvesting is to integrate different energy harvesting mechanisms together and exploits their advantages at the same time [128–140]. Thus, more than two electrical outputs are produced simultaneously, which actually enlarge the output performance further. Fig. 6(a-i) shows a triboelectric-piezoelectric hybrid nanogenerator [49]. A piezoelectric film made of PVDF was bent and placed atop a surface-textured PDMS film to form an r-shaped structure. The PVDF film was double-side coated with Al membrane serving as electrodes, while bottom Al membrane and PDMS film formed the triboelectric pair. When a compressive force was applied to r-shaped PVDF film, it was pressed to contact and friction the surface of PDMS, which generated the triboelectric output. In the meantime, the deformation of PVDF film generated the piezoelectric output. This unique r-shaped hybrid nanogenerator was also demonstrated to be integrated with a keyboard to harvest the typing energy in daily use, which was attractive for further applications. Fig. 6(a-ii) shows a micro-cable structured textile for simultaneously harvesting solar and mechanical energy [88]. In this work, lightweight polymer photoelectric fibers made of ZnO/dye were woven with fiber- TENGs by using shuttle-fling process to form a 320 µm-thick flexible and foldable fabric. This smart fabric can be used to harvest solar energy and mechanical energy at the same time, and is easy to be integrated into various cloths. With a 4 cm × 5 cm fabricated fabric, a 2 mF capacitor can be charged up to 2 V within 1 min, which showed a remarkable charging ability. Fig. 6(b) shows a hybrid triboelectric-piezoelectric-pyroelectric nanogenerator for scavenging mechanical and thermal energies [140]. This hybrid nanogenerator integrated three energy harvesting techniques, which further enhanced the electrical output capability.

The idea of all-in-one energy unit is to provide a solution for the conflict between electrical pulse output of energy harvesters and direct-current power requirement of commercial electronics [141]. Fig. 6(c) shows one prototype of all-in-one energy unit, where the electrical output of energy harvester was firstly treated by a power module circuit, typically including rectification and filtration, and then the modified electrical output was delivered to an energy storage device [142]. Another prototype of all-in-one energy unit is similar in component configuration, but energy harvesters and energy storage devices were further integrated, as shown in Fig. 6(d) [143]. In this work, a CNT/paper-based supercapacitor packaged with PET/ITO films was placed in the middle of arch-shaped TENG. The microstructured surfaces of PDMS were deposited with thin fluorocarbon layers by C_4F_8 plasma treatment process. Thus, ITO films and fluorocarbon polymer layers composed two triboelectric pairs and actually formed two TENGs. When a periodical external force was applied, the electricity generated by TENGs was continuously collected and stored by the supercapacitor. Moreover, power management is widely studied to strengthen the output performance of TENG on external loads, which can be used to increase the effective utilization rate of output electric power [188–191].

In addition, as a complementary of the all-in-one concept, it is worth mentioning that the multiple-function sensors based on TENG have been reported [103,180,186]. Particularly, the hybrid mechanism of all-in-one energy harvesting provides a promising approach to the purpose of multiple sensing simultaneously [129,131,135]. As a new tendency of TENG development, a field called tribotronics experienced a rapid growth in the past three years. By coupling triboelectricity and semiconductor, a "gate" function can be realized to tune/control electrical transportation and transformation [192]. Several types of tribotronic demos have been developed to serve as logic circuits, electronic skins, etc [193–201]. This technology extends the application range of TENG in many fields, including sensing, energy harvesting, human-machine and so on. In addition, one of interesting TENG research topics is the biological application, including energy harvesting, active sensors and so on [202–204]. Some other development trends could be found in the recently published review articles [24,141,205–218], especially the book of Ref [219].

5. Prospect: "All-in-One" self-powered microsystems

As an attractive vision of the foreseeable future, here we propose a new concept of "All-in-One" self-powered wearable microsystem, as shown in Fig. 7, where the "all-in-one" hybrid energy harvesting mechanisms and the "all-in-one" energy unit are further integrated with other functional electronic components to sense and respond the environmental and biological changes. By using the ambient energy harvesting technologies summarized in the above sections, the biomechanical energy and the thermal dissipation from human beings could be efficiently converted to electricity. Different energy harvesting approaches can be combined to accumulate multiple forms of energy at the same time to achieve better electric output performance, which is called "all-in-one" hybrid energy harvesting. The generated power is to be managed by the "all-in-one" energy unit to form a direct-current which can be directly utilized to support the function of the whole microsystem. Furthermore, functional components composed of sensing and processing are integrated with energy harvesters into self-powered microsystems. More importantly, some sensing functions can be realized by energy harvesters themselves too by employing the quantitative relation between external stimulation inputs (i.e., changes of temperature, pressure, motion, etc.) and electrical outputs (i.e., electric signals), as shown in Fig. 4. As for processing functions, the electrical signals of energy harvesters can be used directly to drive various types of actuators as shown in Fig. 5, and also can be managed and stored to power them. In summary, the combination of sustainable power supply and diverse functions realizes an "All-in-One" self-powered microsystem, which enables it to sense both external environmental changes and internal biological information, and to work autonomously and independently. The design and manufacturing of such complex, highly integrated "All-in-One" microsystems obviously pose challenges with regards to packaging, a topic that should be the focus of future R&D and is not covered in this review. It is believed that these wearable "All-in-One" self-powered microsystems will have an attractive potential and will lead to a milestone innovation in multi-disciplinary domains, such as IoT, personal electronics, biomedical microsystems, and so on.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2018.02.046.

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