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Review

Triboelectric nanogenerators for human-health care

Hao Wang [a], Jia Cheng [a,*], Zhaozheng Wang [a], Linhong Ji [a], Zhong Lin Wang [b,c,*]

[a] *State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China*
[b] *Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China*
[c] *School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA*

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ABSTRACT

Since the world's first triboelectric nanogenerator (TENG) was proposed in 2012, numerous TENG-based devices and equipment have sprung up in various fields. In particular, TENG has great potential in the field of human-health care due to its small size, self-powered and low cost. With the continuous deepening of TENG research, its structure, function and technical concept are becoming more and more abundant. In order to summarize the progress and development status of TENG in health care, based on the different types of applications subdirection, this paper reviews the TENG-based research work of this field in recent eight years. The characteristics of various types of TENG-based applications and their corresponding technologies are introduced and analyzed, under the comparison of their structure and performance. This review is dedicated to provide reference and inspiration for the future development and innovation of TENG for health care.

1. Introduction

Since ancient times, human beings have never stopped pursuing a broader, more efficient, more convenient and high-quality means of improving health. However, despite the highly developed material life today, sub-health is becoming more and more common in human groups. As a result, today's people are putting ever higher demands on their health. In this process, the rise of high-technologies such as special materials, intelligent control and new energy sources has provided necessary technical support for the rapid development in medical treatment. As an important part of medical science, human health care is increasingly valued by researchers around the world. A large number of devices with different forms and functions have been proposed and used for the improvement of human health.

However, once the device involves direct use by the human body, it is inevitable to face two key issues: device miniaturization and battery life. Although the production and application of lithium batteries are very mature now, they still need to face the objective fact of limited capacity. For example, the battery life of a cardiac pacemaker is 6–10 years [1], while the battery life of a brain pacemaker (DBS) is only 3–5 years [2]. Therefore, the risk and cost of patients will be further increased by replacing the device. It can be seen that the energy quality, production cost and convenience directly determine the universality of a device. Therefore, finding a new technology that can improve the continuous working ability of the device as much as possible while maintaining the working performance has become the key problem to be solved urgently.

For the energy supply of health care devices, researchers gradually put their sights on the human body itself and conducted a large number of studies on capturing human body energy. For example, some energy collectors based on the principle of galvanic cells can harvest energy from the oxidation process of glucose [3]. However, by reviewing these results, it is obvious that the use of chemical energy often meets many limitations such as slow process, low voltage and always having to be implanted. Moreover, it might be an intuitive judgment of most researchers that the richness of available biochemical energy is far less than human mechanical energy. Therefore, researchers have carried out a lot of attempts on human mechanical energy harvesting. Initially, nanogenerators based on the piezoelectric effect, as an emerging technology that received high attention, were quickly widely used for the collection of mechanical energy in various body parts. It utilizes the piezoelectric and semiconductor properties of a special nanomaterial zinc oxide (ZnO) to achieve the harvesting of mechanical energy such as bending and compression. In 2001, Zhong Lin Wang's team [4] proposed that the ZnO semiconductor material band appeared in *Science*, which attracted great attention and triggered a wave of discussions on nanogenerators. In 2010, his team went a step further and proposed a nanogenerator with flexible fibers that can generate macroscopic piezoelectric potential

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* Corresponding authors.
E-mail addresses: chengjia@tsinghua.edu.cn (J. Cheng), zhong.wang@mse.gatech.edu (Z.L. Wang).

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energy when subjected to unilateral pressure [5], providing new ideas for wearable devices. At the same time, some implanted nanogenerator devices have also made great progress in animals. For example, the single-line generator driven by the mouse heart has achieved effective output [6], which, from a technical perspective, laid the foundation for self-powered pacemakers.

To sum up, what we hope to achieve through the above-mentioned piezoelectric application is to convert tiny or low-frequency mechanical motion into electrical energy. However, in practical applications, the choice of piezoelectric materials often has great limitations. And these materials are often not ideal in terms of flexibility, elasticity, transparency, biocompatibility, etc. In addition, the difficulty and cost of material acquisition and processing are relatively high, further increasing the threshold and difficulty of research and development of devices. Therefore, researchers have to find a better alternative technology. In response to this demand, TENG came into being. In 2012, Zhong Lin Wang's team proposed the world's first TENG [7]. Since then, TENG-based applications have continued to emerge in various fields, which of course also provides a new choice for health care applications. Many of the previously difficult-to-use physical or physiological energy of body now have new possibilities to be harvested and reused. This discovery has greatly stimulated the research enthusiasm of researchers. A variety of TENG-based health care devices and technologies have been continuously proposed. Although since then, other types of energy-harvest devices are still continuously proposed, such as subcutaneously implanted photovoltaic (IPV) elements to harvest solar energy for pacemaker [8], etc., TENG has already be considered as an ideal power source for biomedical electronics [2].

On the other hand, with the deepening of TENG research, both the quality and quantity of papers produced around the world in health-monitoring field have been greatly improved. The large variety, wide range and different performances have caused dazzling beginners. However, there is currently no prior work to systematically organize the progress in this field. Therefore, it is very necessary to classify and sort out important discoveries and inventions in this field in order to carry out further research and development. Taking different functions as the starting point, this paper reviews and discusses the TENG-based application for human health care in the past eight years. The aim is to show the research achievements more intuitively and to provide guidance for more targeted and innovative future research of health monitoring.

2. Principle of TENG

Triboelectrification is a well-known phenomenon. It is a kind of charging effect caused by contact, that is, after the separation of two contacted different materials, they will become electrically charged [9]. It is generally believed that when two different materials come into contact, a chemical bond will be formed between the two surfaces. The charge then moves from one material to another to balance the electrochemical potential difference. These transferred charges may be electrons, ions or molecules. When the two materials are separated, some bonding atoms tend to retain extra electrons, while others tend to lose electrons, which possibly cause the triboelectric charges on the material surface. The presence of a triboelectric charge on the surface of the dielectric could be a driving force for driving the flow of electrons in the electrode to balance the resulting potential drop [10].

Based on above principle, four different TENG modes have been invented, as shown in Fig. 1: vertical contact-separation mode, lateral sliding mode, single-electrode mode, freestanding triboelectric-layer mode.

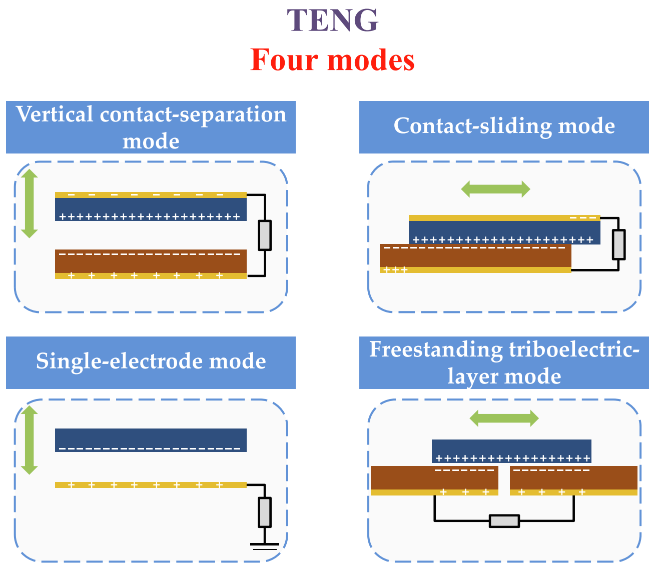


Fig. 1. (Color online) Four TENG modes: vertical contact-separation mode, lateral sliding mode, single-electrode mode, freestanding triboelectric-layer mode.

3. Development of TENG-based application for human-health care

Since Zhang's team [11] first proposed the concept of combining TENG with health care in 2013, increasing number of self-powered devices to improve human-health care services have entered people's horizons. Related papers have been growing rapidly year by year. With the advancement of research, researches have gradually changed from simple, non-implantable and non-degradable applications to multi-disciplinary, implantable and biodegradable ones. More and more research groups have joined the leading queue in the innovation and practical application of TENG. They have continuously proposed new design and technical concepts for TENG-based health care. Many new applications and technologies have more flexible, more accurate and more interdisciplinary design concepts than conventional sensors or power sources. These achievements need to be carefully reviewed and reclassified to summarize more commonalities and explore more specificity.

In the review, we select representative and reliable researches for analysis. In other words, the health care scene of some TENG-devices is only an incidental, optional, non-exclusive assumption in these papers. It itself does not have the qualification for being a specialized health care device. Such devices are generally early designs. If they are really applied to health care, it often brings problems such as rigorous structure, inconspicuous effect, large signal processing equipment (for wearable device) and no experimental verification of implant safety. Therefore, these devices were distinguished and eliminated (among these, some will be re-entered into the field after subsequent upgrades by the same team, so the elimination work also avoids repeated discussions of similar products).

In the end, the research we selected should be able to represent the latest progress and cutting-edge design at that time. The paper needs to have a considerable influence on the future development of TENG in this field. Therefore, this review covers important papers published by different research groups around the world from 2012 to 2019. These achievements include a large number of wearable, implantable and other forms of Human-health Care devices and technologies.

Therefore, this review attempts to use TENG's functions in health care devices as the basis, and divides the applications involved into “TENG-based human-health monitoring applications”, “TENG-powered human-health care applications”, “TENG-based human-computer interaction applications” and “other TENG-based human-health care related applications”. The outline of this review is shown as Fig. 2. In the following, the applications and technologies of the TENG-based application are newly classified. The development process is explained in detail. Some analyses are made on the current status and future potential of TENG related health care development. Through this review, the most critical information such as material selection, structural parameters and output characteristics of the devices involved can be easily obtained. A clearer understanding of TENG devices and technologies in different categories can be established. Finally, this review expects to provide inspiration and guidance for future research innovation and productization.

3.1. TENG-based application for human-health monitoring

3.1.1. Human-health monitoring

The basic physiological characteristics of the human mainly include parameters such as body temperature, blood pressure, heart rate, oxygen consumption and blood glucose. These physiological characteristics are the manifestations of human biological activities and can reflect the changes that occur inside our body. Because basically not affected by subjective factors, it is a common indicator for objectively evaluating human status. At the same time, it can also be used as the essential basis for human health [12]. Therefore, if the human body information, especially the patient’s physiological information, can be collected conveniently and accurately, it will effectively help to find, feedback and solve problems in a timely manner, thereby protecting people’s health.

Human health monitoring (or health monitoring) includes the process of collecting, quantifying, and processing various bioelectrical or non-electrical signals and other parameters generated by human activities, metabolism, etc. [13]. As mentioned above, it involves the intersection of multiple technologies, such as sensing, control, electronic circuit technologies, biomedicine, signal analysis and processing and so on. And such a monitoring system will not only be suitable for the daily pathological monitoring of ordinary people and patients, but also for certain professions in which one may have to be highly active and are prone to dangers, such as a soldier fighting the enemy, fire fighters, law enforcement personnel, miners, deep-sea divers and astronauts in space [14].

Fig. 2. (Color online) Variable TENG-based applications for human health care.

In conventional monitoring systems there are always too many hampering wires, which are meant for acquiring physiological signals. And the system is too bulky to be used for wearable applications [15]. Therefore, developing a portable, safe, sensitive, low-cost, self-powered health monitoring system will be the key to improving human health. Based on this demand, TENG has shown great advantages in the application in this field. Its characteristics are excellently suited to the many needs of physiological information monitoring. Therefore, many researches on TENG in this field have been carried out. Significant progress has been made over the years.

It should be pointed out that, unlike the classification “Health care applications with a TENG-based power source”, this type of TENG applications will directly use the TENG output as a signal, rather than using TENG as a power source for other devices, which indirectly achieve monitoring or medical treatment. At the same time, different from the other category “TENG-based applications for human–computer interaction”, human health monitoring often only includes the output of non-subjective, non-logical content (such as physiological signals), while human–computer interaction (HCI) application includes logical content (such as keys information). The specific differences will be explained later.

3.1.2. Development of TENG-based human-health monitoring application

Human-health monitoring devices often require highly sensitive signal sensors, which convert body signals into electrical signals and transmit them to signal processing terminals. However, as mentioned above, this type of device is often restricted by power supply and has to be used in specific places, thus losing convenience. To solve these two problems at the same time, TENG began to attract the attention of researchers. Its self-powered characteristics perfectly fit the sensitive and portable needs of human physiological monitoring. In addition, it often shows great advantages in economic cost. In the early research of TENG-based health monitoring, many researchers first started with the wearable devices that are most easily combined with TENG, and attempted to collect physiological or body movement information.

In the research process, due to the particularity of wearable devices, it is necessary to comprehensively consider the requirements of comfort, convenience and economy. And among these requirements, the flexibility is the key to achieving comfort. In the predecessors’ work, many researches on flexible sensor have been carried out for health monitoring around world. These devices are often based on piezoelectric effects or chemical batteries [5,16–21]. However, the emergence of TENG in 2012 [7] provides a totally new option for flexible health monitoring devices.

In 2013, Zhu and co-workers [22] disclosed a self-powered insole using polytetrafluoroethylene (PTFE) as triboelectric material. Then in August, new progress was released as shown in Fig. 3a [23]. The reason why this insole needs a folded structure is due to some limitations of PTFE. As a plastic, PTFE is a highly negative material in the triboelectric serie [31], but its mechanical properties are poor, that is, poor flexibility [32]. If the thickness is sacrificed to enhance flexibility, the contact layer will not be able to withstand the severe wear and tear caused by walking. Therefore, in the case that a thick PTFE cannot obtain the ideal flexibility, an auxiliary material “Kapton” and a folding structure are needed to achieve a spring-like effect. The experimental results show that the maximum output voltage is 220 V and the short-circuit current is 600 mA, which can monitor the walking status of feet. Although the structure is relatively simple and the function is relatively

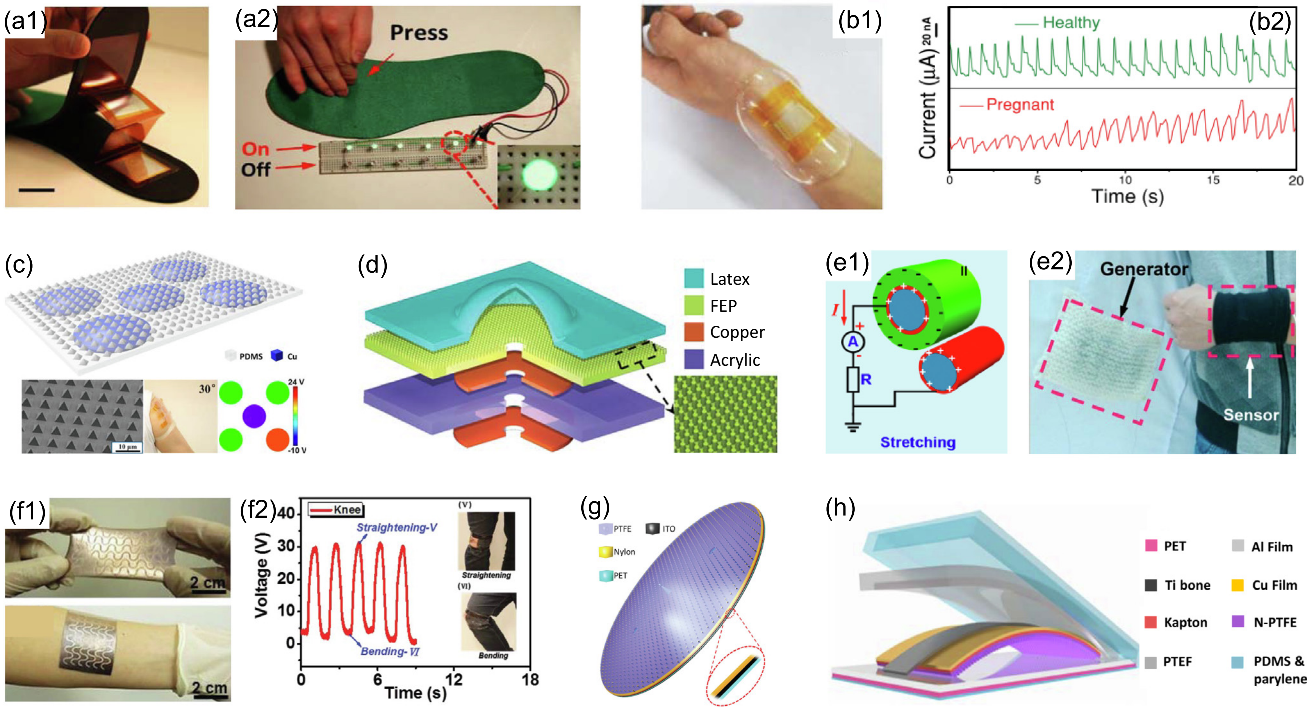


Fig. 3. (Color online) (a1) TENG based insole with folding structure. (a2) Photograph of lighted commercial LED bulbs as driven by the TENG when pressure is applied by human fingers. Reprinted with permission from Ref. [23], Copyright © 2013 Elsevier. (b1) Photograph of an E-skin device for detection of wrist pulses. (b2) Original signals of *I-t* curves for monitoring wrist pulses of a healthy person and a pregnant woman. Reprinted with permission from Ref. [24], Copyright © 2014 Wiley. (c) TENG with pyramidal pattern. Reprinted with permission from Ref. [25], Copyright © 2014 American Chemical Society. (d) Latex layer with arch-structure as a pressure sensor. Reprinted with permission from Ref. [26], Copyright © 2014 Wiley. (e) Fiber-type TENG. Reprinted with permission from Ref. [27], Copyright © 2014 American Chemical Society. (f) Stretchable patch-type TENG. Reprinted with permission from Ref. [28], Copyright © 2015 Wiley. (g) Eardrum inspired membrane TENG. Reprinted with permission from Ref. [29], Copyright © 2015 Wiley. (h) Multilayer structure of TENG cardiac monitor. Reprinted with permission from Ref. [30], Copyright © 2016 American Chemical Society.

basic, it is still one of the pioneers of TENG in the field of health monitoring. However, this form of monitoring device involves only human torso activity, which cannot be used to monitor body's small or internal physiological activities. Therefore, research work on this was proposed immediately. In December of the same year, a flexible, sensitive, and stable electronic skin was proposed for monitoring human physiological signals, as shown in Fig. 3b [24]. Polydimethylsiloxane (PDMS) was selected as the triboelectric material for this device due to its transparent, non-toxic, stable and high flexibility. Additionally, since the device is only used to monitor light signals such as pulse and throat vibration, it can achieve higher flexibility by reducing the thickness of the triboelectric layer to a large extent. In the end, the PDMS used was only 200 μm. Experiments show that the output current reaches 80 nA during pulse measurement, which can accurately distinguish the difference between healthy and pregnant pulses. The proposition of this device provides a reference for a large number of subsequent physiological monitoring devices.

After a year of accumulation, a variety of achievements have appeared in the eyes of the world, leading more and more researchers begin to recognize and study TENG. As the TENG principle gradually became clear, more and more simplified and high-precision design solutions were proposed. However, the inertia of the foregoing research also led to the emergence of too many similar monitoring devices directly attached to the human skin, which to a certain extent weaken the diversity of device design [33–36]. In 2014, Yang and co-workers [25] proposed a human–machine interfacing motion sensor based on flexible TENG (although it is expressed as a human–computer interface, in fact, the signals collected are non-intuitive and non-logical). So they should be regarded as health monitoring devices. The difference between the two is briefly explained in Section 2.1.1, as shown in Fig. 3c. The only material of the triboelectric layer is PDMS, combining with copper (Cu) foil as an electrode to form a single-electrode TENG. There is a pyramid-shaped pattern on the surface of PDMS to improve the output of TENG. Because other research has shown that a TENG with a pyramidal pattern can produce a higher output than a TENG with a cubic pattern [37]. The device will be directly worn on the shoulders or elbows. Through the contact and separation between the PDMS layer and the human skin, the information of body motion is detected. Finally, by combining the fast Fourier transform (FFT) technique and a signal processing system, the device can accurately record the motion of human joints, such as the elbows, knees, heels and even fingers. Experimental results show that the maximum output voltage of the device is 42.6 V, the current density is 1.071 μA/cm^2, and the signal-to-noise ratio is up to 1000. This high sensitivity makes TENG a step closer to the practical application of health monitoring. On the other hand, a patch-type TENG with a similar structure has also been applied to devices for measuring physiological information *in vivo*. In June 2014, Bai et al. [26] tried to use fluorinated ethylene propylene (FEP) as a triboelectric material for pressure sensor, as shown in Fig. 3d (FEP is an alternative to PTFE, which is also transparent, light but easier to process than PTFE) (http://web.archive.org/web/20100724195156/http://www.texloc.com/closet/cl_fep_properties.htm). This TENG utilizes the flexible latex and an arch structure to generate contact and separation with FEP. In the experiment, measurement of breathing and heartbeat was realized. And the pressure detection resolutwion could reach 0.34 Pa.

Although the above-mentioned patch devices have achieved some satisfactory results, once the area is increased, warpage due to insufficient flexibility of the material will inevitably be caused.

As a result, the device cannot fit the body or clothing well, which leads to wearing discomfort. So some researchers were inspired by textiles and developed a variety of fiber-based TENG devices [38–40]. In April 2014, the fiber-like wearable electronic medical device proposed by Zhong and co-workers [27] was one of the earliest representative results, as shown in Fig. 3e. The contact materials are PTFE and carbon-nanotube coated cotton thread. In the experiment, it is possible to detect the motion/vibration of wearing body parts, which can also be converted into electricity with an average output power density of ~0.1 μW/cm^2. By the way, this team also made a strain sensor using the same structure [41]. It should be noted that, because the textile-structure frees the design of the contact layer from the rigidity of the entire surface area and brings it into fiber units, the textiles like devices have totally different sources of flexibility than the patch devices. This means that its flexibility is no longer directly related to the area and thickness of TENG, which provides new possibilities for other material applications that are less flexible than PDMS. It also has to be noted that due to the existence of its fiber structure, although the surface area of the material is increased, the contact of the fiber unit is approximately a line contact. Too much ineffective area leads to a reduction in output capacity. Therefore, although the fiber-based TENG device proposed in this paper has unique ideas, it still needs a lot of deeper work to balance the structural flexibility and effective contact ratio in order to have more practical application value.

In 2015, the application of TENG for health monitoring tended to be stereotyped, highly converging into wearable patch devices, which occupied the leading position of TENG-based health monitoring device. In February of that year, Yang and co-workers [28] demonstrated a self-powered biomedical monitoring device with Kapton as a triboelectric material (one of the best organic polymer materials with comprehensive performance, which has the advantages of high thermal stability, low temperature resistance, high strength, good dielectric properties and high biocompatibility), as shown in Fig. 3f. In experiments, its maximum output voltage reached 700 V and its maximum short-circuits current reached 75 μA. At the same time, Yang and co-workers [29] took inspiration from the human eardrum membrane and disclosed a self-powered sensor for cardiovascular system characterization and throat-attached anti-interference voice recognition, as shown in Fig. 3g. The recognition function of the sensor is realized by a contact and separation TENG composed of PTFE and Nylon. The experimental results show that although the output signal intensity is not particularly high, its signal change has sufficient resolution to successfully complete tasks such as cardiovascular system characterization measurement and throat speech recognition. In particular, the speech recognition function proposed also adds a new application field for TENG, human–computer interaction. However, although the wearable patch-type TENG devices are developing in the direction of lighter and thinner structures, stronger ductility, higher fatigue life, stronger signals, higher accuracy and new materials, the device are still obviously stereotyped, resulting in little development space left for common patch devices. Therefore, researchers have to rethink the innovation direction of TENG in this field. As a result, the development in 2015 experienced stagnation. The number of achievements of TENG-based health monitoring in the whole year reached a trough.

Until 2016, after a long accumulation, TENG-based health monitoring applications ushered in a period of rapid development. The most important progress during this period is that TENG monitoring devices are beginning to move towards implantable devices. In June, Li's team [30] proposed a new self-powered wireless cardiac monitoring, as shown in Fig. 3h. Implanted devices are different from wearable devices, which would be directly in the internal environment of the living body, so their structure and function must be carefully designed. Fully combining the research work of previous people, this implanted TENG device was designed into a multilayer composite structure. The encapsulation of parylene, PDMS and polyethylene terephthalate (PET) ensure the biocompatibility, flexibility and fatigue life of the device. By combining the implantable wireless transmitter (iWT), the power management unit (PMU) and the wireless transmission signal (WTS), the wireless measurement of the heart rate is finally achieved. The results of implantation in living mice showed that the output voltage could reach 14 V and the output current could reach 5 μA. Compared with the output performance of biomechanical energy conversion devices, its output voltage and current have been enhanced by factors of 3.5 and 25, which is a significant improvement. Two months later, this team gave another implanted device using PTFE for heart rate monitoring, but the only difference from the former was the structural form (from an arched structure to a spacer to generate contact and separation). Therefore, no more discussion is given here, only a schematic diagram of the structure is shown as Fig. 4a [42]. In addition, another paper of this team conducted verification experiments on the corrosion resistance and working life of the above package structure in a humid environment. And the results showed that it can maintain stable operation for more than 30 d [50]. The above works done by the team finally converged on the designed multi-level TENG. In practice, the complementary advantages of each material were realized. The reconsidering of more reasonable roles and functions of different materials contributed to optimization of the performance of implantable TENG.

Another important progress is to break through the limitation that TENG always consists of solid materials. Thoughts on the application of liquid materials in TENG have sprouted, making attempts on liquid–solid health monitoring devices instead of conventional patch-type one. In 2016, a capsule-shaped TENG device using conductive liquid and rubber was proposed, as shown in Fig. 4b [43]. In fact, unlike what was expected, this TENG with liquid phase did not really achieve triboelectric charging between solid and liquid, but only used the liquid electrode. In the experiment, only the basic function of monitoring the human torso motion was realized (some other teams have done similar work to enrich the application scenario [51]). But it is undeniable that this is an essential attempt on liquid materials, providing inspiration for the research of real solid–liquid TENG devices. In addition, the electric eel-skin-inspired TENG electronic skin proposed by Lai and co-workers [44] also promoted the development of solid–liquid TENG, as shown in Fig. 4c. Two years later, this team showed an improved product [52]. This TENG uses a PDMS structure that wraps percolating silver nanowires (AgNWs) networks to achieve extremely high stretchability. It is also used to monitor human torso motion. Although AgNW is not a liquid, its combination with PDMS is very close to the solid–liquid TENG flexible device proposed by later research, which is also inspired by electric eel. Therefore, the above researches both have contributed to the research of non-full solid TENG from different perspectives.

Of course, some conventional TENG health monitoring devices have also been developed and optimized during this period. For example, the application scenarios of patch-type devices have been broadened, which can be made into a sleep posture monitoring system [53]. There are also optimizations of the material universality and structural size of fiber-based TENG devices to make them more easily integrated with normal clothing products [54–56].

The development of things is often spiral and iterative. After a period of rapid development, the research of TENG health monitoring devices slowed down again in 2017. Most researches are the improvement of previous work, the realization of extreme or special properties or new material choices, etc. For example, focusing on signal transmission, Shi et al. [57] demonstrated a health monitoring device that can be self-powered to achieve wireless

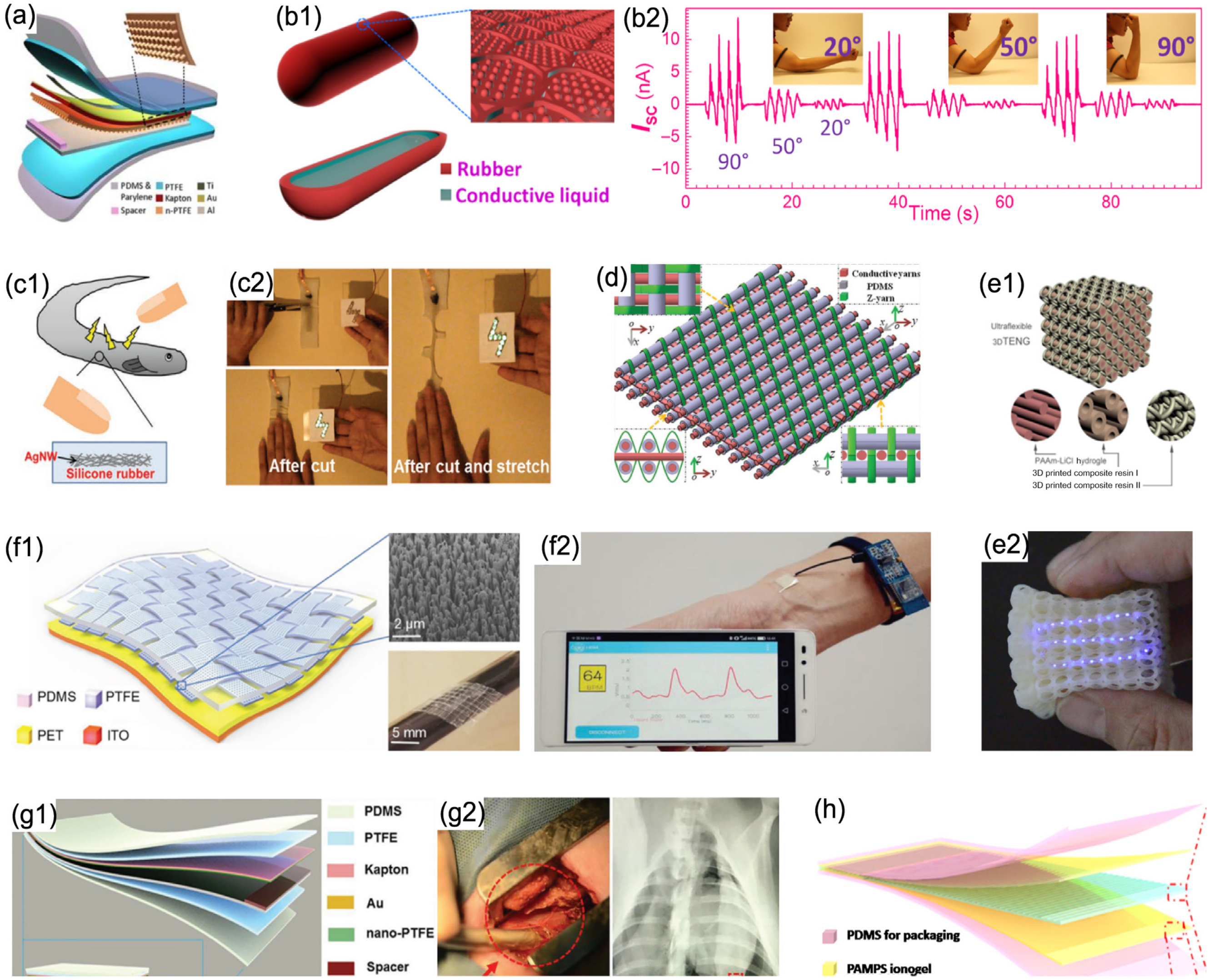


Fig. 4. (Color online) (a) Multilayer TENG cardiac monitor with a spacer. Reprinted with permission from Ref. [42], Copyright © 2016 American Chemical Society. (b1) Capsule-shaped TENG device with liquid electrode. (b2) Response of the TENG to different bending angles. Reprinted with permission from Ref. [43], Copyright © 2016 AAAS. (c1) Electric eel-skin-inspired TENG. (c2) Photograph demonstrating that the device can drive a load and retain its stretchability even experiencing severe tear damages. Reprinted with permission from Ref. [44], Copyright © 2016 Wiley. (d) "3D" orthogonal woven TENG. Reprinted with permission from Ref. [45], Copyright © 2017 Wiley. (e1) Foam-structure ultraflexible TENG. (e2) Photographs of the device after compression. Reprinted with permission from Ref. [46], Copyright © 2018 Elsevier. (f1) Blood pressure sensor with ITO electrode. (f2) Photographs showing that the low power consumption sensor system is worn against wrist. Reprinted with permission from Ref. [47], Copyright © 2019 Wiley. (g1) Heartbeat monitor implanted in a pig. (g2) Photograph of minimally invasive surgery with a DR image of the heart implanted a device by integration with a surgical delivery system. Reprinted with permission from Ref. [48], Copyright © 2019 Wiley. (h) Transparent and stretchable TENG. Reprinted with permission from Ref. [49], Copyright © 2019 Elsevier.

transmission. The wireless transmission efficiency achieved 26.6% with a 16 cm^2 receiver while the distance is 1 cm. In pursuit of higher sensitivity and practicality, Ouyang et al. [58] proposed a new wearable sensor for antidiastole of cardiovascular disease. With excellent output performance (1.52 V), high peak signal–noise ratio (45 dB), long-term performance (107 cycles), and low cost price, this device is highly representative in pulse monitoring research. As for extreme properties, the use of polyacrylamide-lithium chloride (PAAm-LiCl) hydrogel combined with PDMS to form ultrastretchable (uniaxial strain, 1160%) and transparent TENG [59]. And crushed-graphene is also used for the same purpose [60]. In addition, research on ultra-thin TENG devices has also been pursued, of which the overall thickness is only 102 μm [61]. Dong and co-workers [45] optimized the weaving and combination of fiber-based TENG and designed a "3D" orthogonal woven TENG with better output performance, as shown in Fig. 4d. Its power density is several times than that of conventional 2D textile TENG. The maximum peak power density of 3D textile can reach 263.36 mW/m^2 under the tapping frequency of 3 Hz. Additionally, there are also examples of making textile-type TENG into a patch-type device, so that it has both the strength and flexibility of textile-type devices and the small size and thinness of patch-type devices [62]. What's more, a team made a foam-based human motion monitor [63]. Although the internal space of the foam was not used in this paper, it gave a chance to another team of using a similar foam-structure to design 3D ultraflexible TENG, greatly increased the effective contact area, as shown in Fig. 4e [46]. In particular, there is a research worth mentioning. The puzzle-type TENG proposed by Deng et al. [64] has a repairable function. Covalent dynamic disulfide bonds in the elastomer matrix can be used to achieve healing and docking of fracture complements under external thermal stimulation, which provides a new idea for extending the product-life of the devices. However, most of the above-mentioned devices are only used for monitoring torso motion, which cannot have various functions like some devices in 2016.

In 2018, TENG research once again made great progress. On the one hand, for some familiar conventional research, researchers continue to search for details that can be optimized for the device. Many of them are similar to the previous work, but outstanding in some particular aspects, which will not be repeated here [52,65–69] (another piezoelectric patch device with reference value in terms of integration [70]). In terms of device function, in October 2018, Meng et al. [47] proposed a flexible TENG device that can measure blood pressure. It uses PTFE and PET as contact layers. Indium tin oxide (ITO) was used as the electrode, as shown in Fig. 4f. It seems to have a fibrous structure, but in fact it is a patch-type device. The purpose of the textile structure is to provide a space for contact and separation. The key-progress of this paper is achieving accurate and real-time measurement of BP, which is a new application scenario. Combining signal processing and Bluetooth module, wireless transmission of blood pressure, pulse and other information can be realized. The results show that within the range of 710 Pa, it has a sensitivity of 45.7 mV/Pa (a wide detection range of ≈710 Pa). And the response time is less than 5 ms.

The most significant achievement of 2019 was that based on the heart rate monitoring TENG device that was implanted in mice two years ago, Li's team [48] successfully implanted an optimized device in a pig, as shown in Fig. 4g. Relying on the improved multilayer structure and PTFE as triboelectric material, the device can output a stronger signal. In addition, based on previous research on the output performance of TENG by plasma surface treatment technology [71], this paper explores and experimentally verifies the effect of surface corona discharge treatment on the contact layer on the performance. The results show that the surface pretreatment technology has a significant improvement in TENG output. In the experiment, the device can successfully monitor physiological activities such as heart rate with a sensitivity of 1.195 mV/mmHg. And all of these works are prepared for the further important application of pacemaker in the future. Some digressions are that even if implanted devices have no battery, fatigue life will still bring product-life issues. If the device is replaced by surgery, the patient will again bear a risk. Therefore, some TENG devices that can be absorbed and degraded by the human body have been gradually developed, which provides support for the application of the above implanted devices [72–76]. Due to degradable materials are selected as the friction layer, these devices are often not directly used to monitor body signals, but are used as power sources for other devices. Therefore, representative results will be discussed in following Section 3.2.2.

In 2019, the homogeneity of researches in this field is still particularly evident. Patch-type torso motion monitoring devices are still the main category [77–84], especially for the finger movement monitoring. And a small number of textile-type devices [85,86]. Only one of them is illustrated here. In February, Zhao and coworkers [49] proposed a transparent and stretchable TENG, which is similar to the aforementioned hyper-stretch devices [59], as shown in Fig. 4h. This device uses poly(2-acrylamido-2-methyl-1-propanesulfonic acid) (PAMPS) ionic gel layer as a new material, which contacts with textured PDMS layer. Because it is only used for sensing, there is no requirement for output power. So no other auxiliary materials are added. Only the patterned PDMS is used to generate a contact-separation effect during stretching. The results show that it can detect trunk movement, breathing and pulse with a sensitivity of 0.39–1.46 V/N in the range of 0.1–1 N. Inspired by the C. zebrine leaf surface, the array of cone-like morphology was used to achieve an increase in sensitivity to PTFE-based TENG output, which is 14 times higher than that of common flat PTFE [87]. Similarly, the research goals of textile-type devices are mostly focused on improving the sensitivity and comfort of the device. For example, in March 2020, the textile TENG device proposed by Fan et al. [88] exhibits the pressure sensitivity (7.84 mV/Pa), fast response time (20 ms), stability (greater than 100,000 cycles), wide working frequency bandwidth (up to 20 Hz), and machine washability (greater than 40 washes). This device can well monitor arterial pulse waves and respiratory signals. These achievements have all contributed to the improvement of the practicability of such devices.

In summary, due to the advantages including simple structure and convenient production, flexible patch-type TENGs have shown strong vitality in the field of health monitoring since the emergence of TENG. As early as 2013, a large number of patch-type TENGs have quickly opened the door of TENG-based body information sensing through various combinations of different clothing (such as clothes, shoes, insoles, bracelets, etc.). However, with the advancement of research, simple patch-type TENGs, only with basic functions, can no longer meet increasing monitoring and comfort requirements. Therefore, various improved forms of TENG began to appear, among which the multilayer composite patch-type TENGs and the textile-type TENGs have shown outstanding performance. The multilayer composite patch-type TENG is an extension of the simple patch-type TENG. Based on the difference performances of multilayer materials, TENG possess characteristics such as biocompatibility, degradable, high-durability, ultra-light, ultra-stretchable and ultra-transparent, so that the patch-type TENG can maintain research interest in the field of health monitoring to now. In particular, the patch-type TENG with biocompatibility provides brand new possibilities for the field of implantable devices. It is the accumulation of years of experience in the research of patch-type technology that has finally brought many successes in implanted devices around 2018. On the other hand, since wearable health monitoring devices often require extremely low output signal strength and show high demand for the convenience and comfort of wearing, textile-type TENG entered the vision of researchers as an alternative to patch-type TENG. However, as the structure is more complicated than patch-type TENG, it is more difficult to manufacture and test. Therefore, although there have been attempts around 2014, it did not have a large number of applications until around 2017. Textile-type TENG has a completely different mechanism of flexibility and can be better integrated with clothing. Furthermore, relying on the upgrading of processing technology and the optimization of materials, the fibers are getting thinner and stronger, and the practicality it brings to the public is also becoming more and more intuitive.

From the above development history, we can clearly see that the development process of TENG for health monitoring has undergone a transition from simple to complex, from wearable to implantable, from single-technology to multi-disciplinary integration, from daily life to the frontiers of medical care. This is also a unified phenomenon in the development of most scientific research undertakings. But at the same time, we should also see the laws behind the ups and downs of the situation experienced during development. The high-yield period of research is often accompanied by high-speed development in the field, while also bound to usher in a research bottleneck. And the period of research downturn usually contains the deepening and innovation, which is often followed by new breakthroughs. In the past eight years, researchers have never stopped to bring the TENG devices for health monitoring into the vision of more people, sparing no effort to make it more and more practical and perfect.

3.2. TENG-powered human-health care applications

3.2.1. Power sources and generators

In fact, power source and generator are two similar concepts. They both convert motive power (such as chemical energy or mechanical energy) into electrical energy for use in an external circuit. However, power sources normally have additional energy storage capacity compared to generators. Therefore, in other words, it can be considered that the generator plus the energy storage device constitutes a power supply device.

As for human-health care devices, due to safety considerations, household or commercial power supplies with excessively high voltages are rarely directly used. As a result, batteries, because of their modularity, portability and practicality, have become one of the most common power supplies. However, although the battery can provide continuous energy and has relatively high energy densities, a certain limitation for its capacity is always there. Inevitably, frequent replacement or recharging is required. This brings many inconveniences to the use of human health devices. For example, most of conventional implanted devices always have to be replaced regularly, which increases the risks and costs of patients to a certain extent. Therefore, developing a self-powered health care system, which can harvest energy from human body or the environment, is a research direction with great significance and practical value.

On the other hand, TENG originally appeared exactly as a new power source. However, largely due to the unsatisfactory output performance in early years, TENG is regarded more commonly as a sensor rather than a generator, just as shown in the previous sections. Although such sensor-oriented applications are highly sensitive now, the application field is still narrow and the function is limited. A large number of more complex functions that require continuous energy supply are difficult to implement. The direct use of TENG output signals has been unable to meet people's further needs for health care. Fortunately, with the deepening of TENG research, its output performance has greatly improved. Researchers are increasingly refocusing on using TENG as an energy supply. This change gradually brought TENG back from the "sensor" field to the original intention of a "generator".

3.2.2. Development of TENG-powered human-health care applications

In 2013, since it was in the early stage of research, the inherent weakness of TENG's low output has not been well handled, resulting in rare application scenarios valid for TENG-based mechanical energy harvest. The most common motion of the human body is walking, so early work naturally converged on the harvest of walking energy. Yang and co-workers [89] proposed a new type of flexible TENG built into clothing, as shown in Fig. 5a. This TENG uses PDMS and Al foil as triboelectric materials to form a contact-separation mode TENG, of which the thickness is only 0.8 mm. In order to improve the output capability, the team made some preliminary attempts on the surface treatment, including generating a fluffy microstructure on the PDMS surface to enhance the triboelectric charge transfer. Experiments show that during normal walking, the maximum voltage and current density of this flexible TENG are 17 V and 0.02 μA/cm^2, respectively, which can directly light up 30 light-emitting diodes (LEDs) or charge lithium batteries indirectly. Although this is a very simple attempt, it becomes a basic form of TENG-based wearable devices. Compared with built-in-clothing devices, although the built-in-soles devices have relatively limited area, they are more direct and simple to combine with walking energy harvest. This team also reported an TENG-based insole, as shown in Fig. 5b [90]. Similarly, the insole uses PDMS (but a new pattern was tried on the surface of PDMS) and PET to form a contact-separation mode TENG. In addition, ITO is used instead of metal electrodes, which is one of the earliest TENG applications using ITO as the electrode material. ITO has both good electrical conductivity and excellent transparency, which enabling wearable devices to achieve their target functions while minimizing the impact on appearance. Its outstanding characteristics have attracted widespread attention from researchers. Experiments show that the maximum voltage and current density reach 220 V and 0.8 μA/cm^2, respectively, which can also light up 30 LEDs or power some small electronic devices such as glucose detectors. In addition to the above two devices, there is also a combination with TENG and backpack for collecting vibration energy during walking [97]. The same structure was again used by another team for an ultralight portable self-powered device 4 years later [98]. All these devices are combined with the human body through the clothing medium. The form is intuitive, the function is basic and the structure is simple.

In 2014, Li's team [91] made great progress in the field of capturing human physiological and mechanical energy with TENG. For the first time, TENG-based device successfully harvest energy *in-vivo*, as shown in Fig. 5c. This implantable device can power a pacemaker by harvesting the mechanical energy generated by respiration. PDMS with pyramid-array pattern and Al foil are used as the triboelectric material to form a contact-separation mode TENG, with gold foil and Al foil as electrodes. The device is encapsulated with a polymer to isolate it from surrounding medium and to improve its robustness. As a result, it became the embryonic form of the multilayer composite structure TENG mentioned earlier. In the experiment, TENG was implanted under the left chest skin of the rat. The inhalation and exhalation of mice will cause the thorax to contract and expand, which in turn produced deformation of the TENG, thereby generating electricity. *In vivo* experiments with mice show that the average output of the TENG is 3.73 V and 0.14 μA. And the power density can reach 8.44 mW/m^2. Five breaths can theoretically drive a pacemaker to work once. Although this attempt did not really connect the pacemaker *in vivo* experiments, it did indeed verify the feasibility of this health care application direction. It is a pioneering achievement for implantable TENG devices, laying a solid foundation for the team's further experiments on live pigs.

In 2015–2016, in addition to the conventional built-in-shoe TENG device was optimized [99,100], with the development of the aforementioned fiber-type TENG health monitoring device, some textile-based power source devices have also emerged. For example, Kim's team [101] demonstrated a type of flexible fiber-based TENG. It can directly drive some other energy-consuming devices, which means the potential to power health care devices. However, although its instantaneous output is not low, it is also extremely unstable. Therefore, in order to achieve a more stable energy supply, energy storage units must be involved. However, despite there are many examples of directly charging lithium batteries [102,103], the charging efficiency is still not ideal enough due to large fluctuations in TENG output. Therefore, as an alternative, there have been many attempts to combine TENG with super capacitors (SC), which has improved the quality of energy supply to some extent [104–108]. There have also been some attempts to combine with solar cells to achieve the simultaneous harvest of mechanical energy and solar energy by fabric devices [109–112]. These devices have their structures with high similarity and just provide some possibilities of serving health care devices. Most of them are not directly applied to health care, so they will not be described in detail.

Researches on implantable devices have been progressing steadily during 2015–2016. Among them, the representative research is the use of TENG to promote cell growth and differentiation. In July 2015, a device for mouse embryonic osteoblasts' proliferation and differentiation is proposed by Tang et al. [113]. TENG composed of PDMS and ITO can support the work of a low-level laser cure system. And it was demonstrated that the system enhanced MC3T3-E1 proliferation by 15% after 2 d of laser irradiation and accelerated the cells' differentiation by 16.9% after 5 d of irradiation. This work was conducted further research in 2019 [114]. Additionally, as mentioned in Section 2.1.2, some biodegradable devices became feasible. Zheng et al. [72] reported a biodegradable

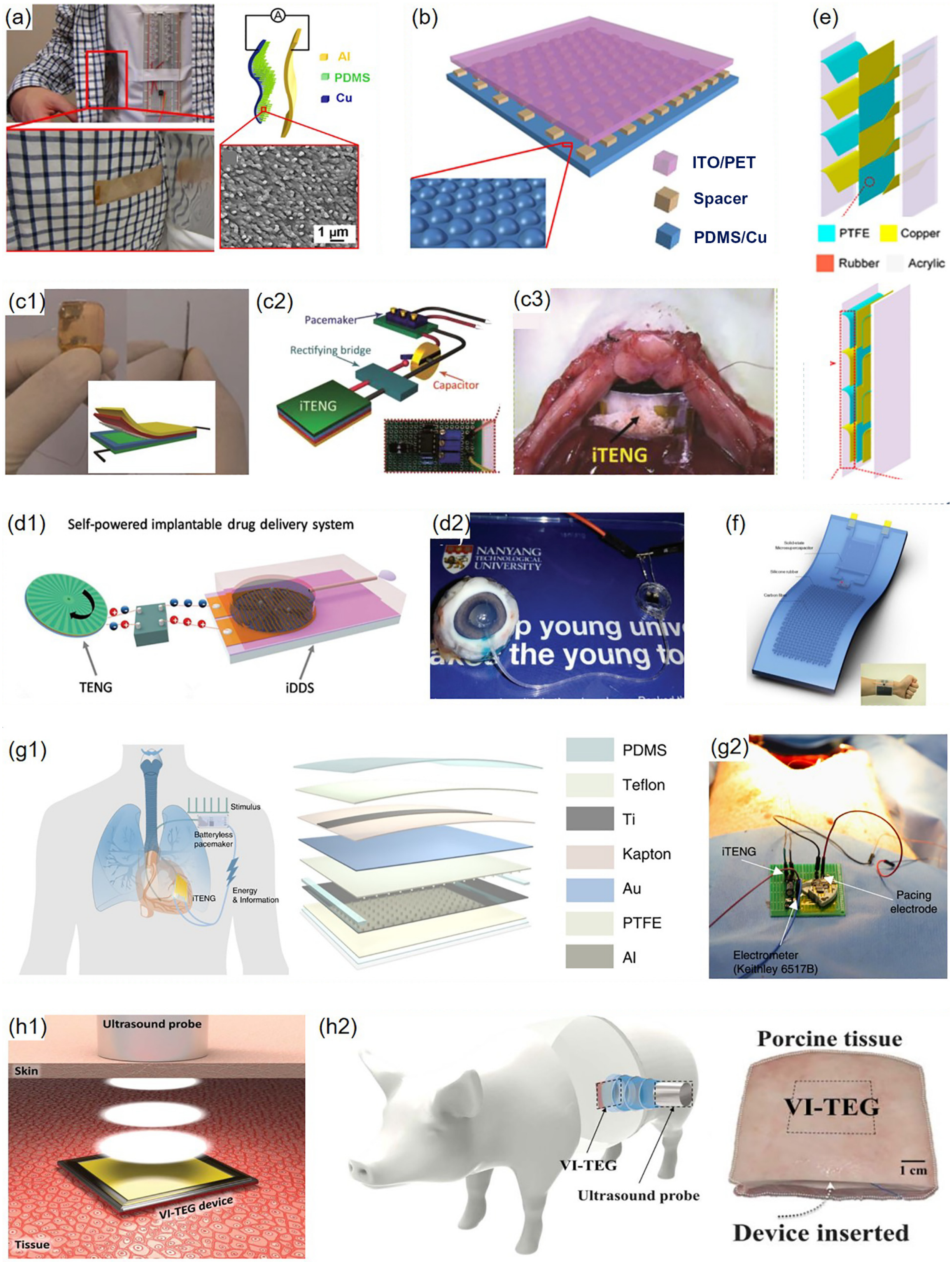


Fig. 5. (Color online) (a) Patch-type TENG device in clothes. (b) TENG-based insole as a power source. Reprinted with permission from Refs. [89,90], Copyright © 2013 Elsevier. (c1) Breathing-driven implantable device which can supply power for pacemaker. (c2) Structure and photograph of the selfpowered pacemaker. (c3) An enlarged picture of the TENG. Reprinted with permission from Ref. [91], Copyright © 2014 Wiley. (d1) Self-powered implantable drug delivery device. (d2) Photograph of the experiment after implantation surgery. Reprinted with permission from Ref. [92], Copyright © 2017 Wiley. (e) Contact-sliding mode TENG harvesting walking energy for commercial sensors. Reprinted with permission from Ref. [93], Copyright © 2017 American Chemical Society. (f) Self-powered bracelet with high integration. Reprinted with permission from Ref. [94], Copyright © 2018 Elsevier. (g1) Beat energy harvesting device for pacemaker with experiment *in-vivo* pig. (g2) Symbiotic cardiac pacemaker system in animal experiments [95]. (h1) ultrasound energy harvesting device (VI-TEG) for pacemaker with high integration. (h2) Schematic of the porcine *ex vivo*. Reprinted with permission from Ref. [96], Copyright © 2019 AAAS.

TENG in 2016. It can power two complementary micrograting electrodes to orientate the nerve cell growth, and can be degraded and resorbed in an animal body after completing its work cycle without any adverse long-term effects. This work was also further studied in 2018 [73]. In November 2016, there was a more innovative implantable device progress. Song et al. [92] proposed a self-powered implantable drug delivery system, as shown in Fig. 5d. The system uses freestanding triboelectric-layer mode layer TENG (PTFE and Cu) to provide the electric energy required for ionization. The bubbles produced by ionization expel the drug for delivery. In the experiment, the drug flow rate can be adjusted by controlling the TENG speed from 5.3 to 40 μL/min. This team demonstrate the *ex vivo trans*-sclera drug delivery in porcine eyes using this TENG-based device by utilizing the biokinetic energies of human hands. Although this device is really far from the conditions for practical production and use, to a certain extent, it opens a new path for the treatment of certain chronic diseases. It should be mentioned here that the freestanding layer mode TENG of device is totally no association with the human body. TENG only plays a role as a generator. In general, the freestanding triboelectric-layer mode TENG often has higher charge transfer efficiency and better output performance than most of the aforementioned contact-separation mode ones. Therefore, it should theoretically provide better conditions for driving other medical devices more efficiently, but actually not. Correspondingly, the disadvantages brought by the freestanding layer structure are also obvious: one is the inevitable increase in the volume of the component; the other is the intensification of the material wear. Therefore, this type of TENG will not be suitable for entering the human body as an implanted device, which is why there are relatively few applications of freestanding layer mode TENG.

In 2017, researchers finally came out of the repeated research of fiber-type TENG energy supply devices that they have been tireless for more than two years. They finally began to calmly rethink about new attempts. Lin et al. [93] proposed a self-powered sensor based on contact-sliding mode TENG, as shown in Fig. 5e. This TENG uses rubber as an elastic part, enabling reciprocating sliding between PTFE and Cu foil. This mode of TENG has similar disadvantages as freestanding layer mode TENG but lower output, so this is a rare successful attempt. Results show that the maximum output voltage of the TENG exceeds 540 V and the maximum output current exceeds 12 μA. When actually worn on the human body for natural walking, the TENG delivered a maximum power of 2.28 mW with total conversion efficiency of 57.9%. By connecting a heart rate sensor and combining a Bluetooth communication circuit, wireless measurement of human physical information such as heart rate can be achieved. On the other hand, there are some examples of TENG combined with other technologies in the year, such as combining with electromagnetic springs [115], with carbon nanotubes [116] and with slime-based ionic conductors [117], etc. They have a certain reference value, but only involve the harvest of human mechanical energy and have no substantial health care application.

The same dilemma as TENG-based human-health monitoring devices also comes to TENG-based power source applications. While wearable TENG-based devices have less and less space for developing, the development threshold for implantable TENG-based devices is still high, which has made the development of devices in this field increasingly slow. There were few high-level achievements in 2018. Jiang et al. [94] successfully combined MXene electrochemical microcapacitors with TENG, making wearable devices more compact. In this device, the TENG part is still in the form of silicone rubber wrapped carbon fiber, which is a single-electrode mode TENG, as shown in Fig. 5f. It uses the excellent electrical characteristics of MXene capacitors to achieve a high degree of integration of the entire device into a bracelet. The output power can be supplied to the electronic watch and the thermo-hygrometer. The experiments show that the maximum voltage is 50 V, the current density is 0.13 μA/cm^2 and the maximum output power is 7.8 μW/cm^2. Although it is also not directly used for health care, its high integration has a very enlightening effect on real-time pulse and blood pressure measurement devices.

Finally in 2019, TENG-powered health care applications ushered in a major breakthrough. Based on years of work, a product called Symbiotic cardiac pacemaker was proposed by Li's team [95], as shown in Fig. 5g. This device is a milestone in the health care application process. It is the first time to implement a true self-powered cardiac pacemaker. This TENG composed of an Al foil and a PTFE film was pre-treated by the corona discharge system. With a very small area, the output open-circuit voltage is as high as 65.2 V. After being implanted in pigs, the energy generated per cardiac cycle is 0.495 μJ, which is higher than the required endocardial pacing threshold energy (0.377 μJ). This is the first time that TENG-based implantable device has been successfully applied to the heart of a pig which is closer to a human. And it has successfully achieved that each heart beat provides enough energy to trigger an endocardial pacing, which means TENG pacemaker is a big step closer to the application to human body. In addition, the TENG has shown remarkable mechanical durability (100 million mechanical stimuli cycles) and cytocompatibility, which are key factors for long-term implantable devices.

Kim and co-workers [97] published the first TENG related paper in *Science*. This paper proposes a device that uses TENG to harvest external ultrasonic energy and recharge the implanted device in the human body, as shown in Fig. 5h. The experimental results show that in pig tissue, the voltage and current generated *ex vivo* by ultrasound energy transfer reached 2.4 V and 156 μA under porcine tissue. It is enough to power low-energy commercial implantable health care devices. Although no verification experiments have been performed on live pigs, the device has demonstrated a high degree of completeness, that is, its excellent integration and efficient performance. These make it very close to practical products. In particular, its output performance enables TENG to compete with piezoelectric technology for the first time, making it truly qualified in the field of biomedical devices.

Looking back the above development process, the development history of TENG as a power source is highly similar to that as a monitoring device, which has been discussed at the end of Section 3.1.2. Somewhat differently, as a power source, it has more application scenarios and also faces more challenges. It can be found that although "Be a generator" is the original intention for TENG, its output performance is still far from satisfactory. After a short development climax in early years (2012–2014), the most direct and easiest patch-type and textile-type TENG-powered devices quickly lost the space for further research. Research on implantable devices became an inevitable trend. And for the transition from wearable devices to implantable devices, the two key issues that need to be handled with are the improvement of the output performance and the integration. Only by overcoming these problems we can make a real breakthrough in TENG-powered human-health care devices. So the overall development of implantable devices is not fast. Until the past three years, these problems are gradually being digested by researchers. Some technologies that enhance the output efficiency of TENG are gradually being proposed. In addition to the surface treatment technology like corona discharge, there are additional technologies such as charge pumps [118–120], current amplification technology using tip discharges [121] and other polarization treatment technology of materials, etc. These have provided technical support for improving TENG's performance from different perspectives. Therefore, an increasing number of implantable devices service for pacemaker and drug delivery are proposed from 2016. Implantable TENG devices are showing increasing value in health care applications.

3.3. TENG-based human–computer interaction applications

3.3.1. Human-computer interaction

The Association for Computing Machinery (ACM) defines human–computer interaction (HCI) as "a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" [122]. Here, we need a more specific and clear definition to delimit the boundary between HCI devices and health monitoring devices. In fact, both HCI and health monitoring devices involve the transmission of information. There is certain homogeneity. The two can be independent of each other or can also be considered as a subordinate relationship. In some simple, basic and undifferentiated cases, the health monitoring system can be regarded as a link of the HCI system without affect the development of their applications. However, this paper should provide a way for more people to understand TENG. And on the other hand, this involves medical devices, which will directly affect human health. Therefore, it is necessary to distinguish between these two types of technology. According to the direction and type of information flow, TENG-based applications can be divided as follows.

Health monitoring devices: focus on visual display unknown information that people cannot directly observe through such devices with computer system. The signals are often objective, non-logical signals such as human physiological activity information.

Human-computer interaction devices: focus on transmission of known information from human mind to computer system through such devices. The signals are often subjective and logical signals such as input instruction information.

Before reviewing, we should realize that because TENG-based HCI devices have more sensing units, more difficult signal processing, more limitations and less direct application scenarios compared to health monitoring devices, it has been developing slowly for many years. And its development depends to some extent on the progress of the foregoing two categories of research. Therefore, the number of progress produced each year is not large.

3.3.2. Development of TENG-based human–computer interaction applications

In August 2013, two papers on the application of TENG for pressure sensing and tactile imaging were published, one based on contact-separation mode and the other based on single electrode mode. They are the typical type of early TENG-based HCI devices [123,124]. As shown in Fig. 6a, b, they can output the location of the designated pressing area. The key information transmission function realized by them has become the main function of most TENG-based HCI devices since then. It should be known that even up to now, although most of this type devices are normally called "Tactile" sensors, in fact, they are closer to "Haptic" sensors.

In 2014, there was no significant achievement different from the aforementioned products. There are only some TENG-based devices that are named the tactile interface, but actually only realize the switching function.

An eardrum-inspired TENG device proposed by Yang and co-workers [29] in 2015 has been introduced, which can be used for health monitoring. This team then published a similar device again, as shown in Fig. 6c [125]. But this time they focused on the acquisition of sound signals for some analysis. Experimental results show that voice signals can be recognized sensitively. Therefore, this device can be used as a human–machine interface for speech recognition. This is one of the early attempts at TENG for speech recognition.

In 2016, several teams optimized the tactile recognition and imaging from different aspects. Among them, Wang and co-workers released two results, respectively, researching high-resolution and high-response haptic sensing matrix [131] and triboelectric luminescence matrix [132]. As a step forward, the two are integrated to make a device that can output both optical and electrical signals without an external power supply, as shown in Fig. 6d [126]. Kim's group [127] improved the adaptability of the device, using a multilayer layer structure to achieve a higher degree of integration, which made it possible to use the device in harsh environments shown in Fig. 6e. Shi et al. [133] contributed to device light weighting, the resolution of which can be achieved 1.9 mm with only 4 terminals. In addition, there are some other attempts such as fully transparent tactile interfaces [134] and electronic transistors tactile interfaces [135], which provides some productization reference for TENG-based tactile interface. In 2017, Li et al. [128] made great contributions to the technology of voice human–computer (HC) interface. They proposed a TENG-based flexible device with both microphone and speaker functions, as shown in Fig. 6f. Normal TENG-based voice HC interface devices can only realize the conversion of sound signals to electrical signals. With the honeycomb structure of the ferroelectret foam, the device not only improves the charge storage capacity but also gives it the ability to change the thickness under the external electrical signals. This controllable change in thickness makes the conversion from electrical signals to sound signals possible. The realization of this technology has further broadened the application scenarios of voice HCI devices, making TENG no longer a pure electrical signal generator, but a real "interactive" center.

Pu et al. [129] found a new idea from the glasses and realized HCI through blinking, as shown in Fig. 6g. This device has two contact-separation mode TENG on both sides of the glasses frame. Electric signals can be generated by the muscle-movements of eyes when blinks. With wireless transmission modules, wireless hands-free typing becomes possible. On the other hand, there are some other attempts on TENG materials (such as paper, silk and nylon that can be repeatedly washed) for HCI, which can be referred to [136–138].

In 2018, Guo et al. [130] proposed a self-powered sound sensor with a fan blade structure, as shown in Fig. 6h. Its fan blade structure makes it have high sensitivity and wide frequency response band. Experiments show that it has a sensitivity of 110 millivolts/decibel and a recognition frequency band of 100 to 5000 Hz, reflecting the potential in robot interaction and hearing aids.

In addition, inspired by other textile wearable devices, Zhou et al. [139] demonstrated a sign-to-speech translation device in 2020. This device uses polyester and PDMS to make composite fibers. It has a recognition rate of up to 98.63% and a recognition time of less than 1 s for 660 language hand gestures. This research gives aphasia patients a new possibility of language expression.

As mentioned above, the application of TENG in HCI is relatively preliminary. Not until 2014 did the patch-type TENGs in this field receive widespread attention. HCI devices often need to invest more research time and inevitably need to combine more technologies in other fields, for example there is already a highly integrated flexible electronic skins which can detect more than 7 types signal [140]. On the other hand, the late start also means that the development potential is large and the developable space is sufficient. Benefiting from the research experience in other directions, the multi-material & multilayer structure have been excellently developed in this field, which can take into account the lightness and convenience while having satisfactory sensitivity. Furthermore, other types of devices (including the above mentioned textile-type device) have also begun to show competitiveness in recent years. With the brightening application prospects of HCI

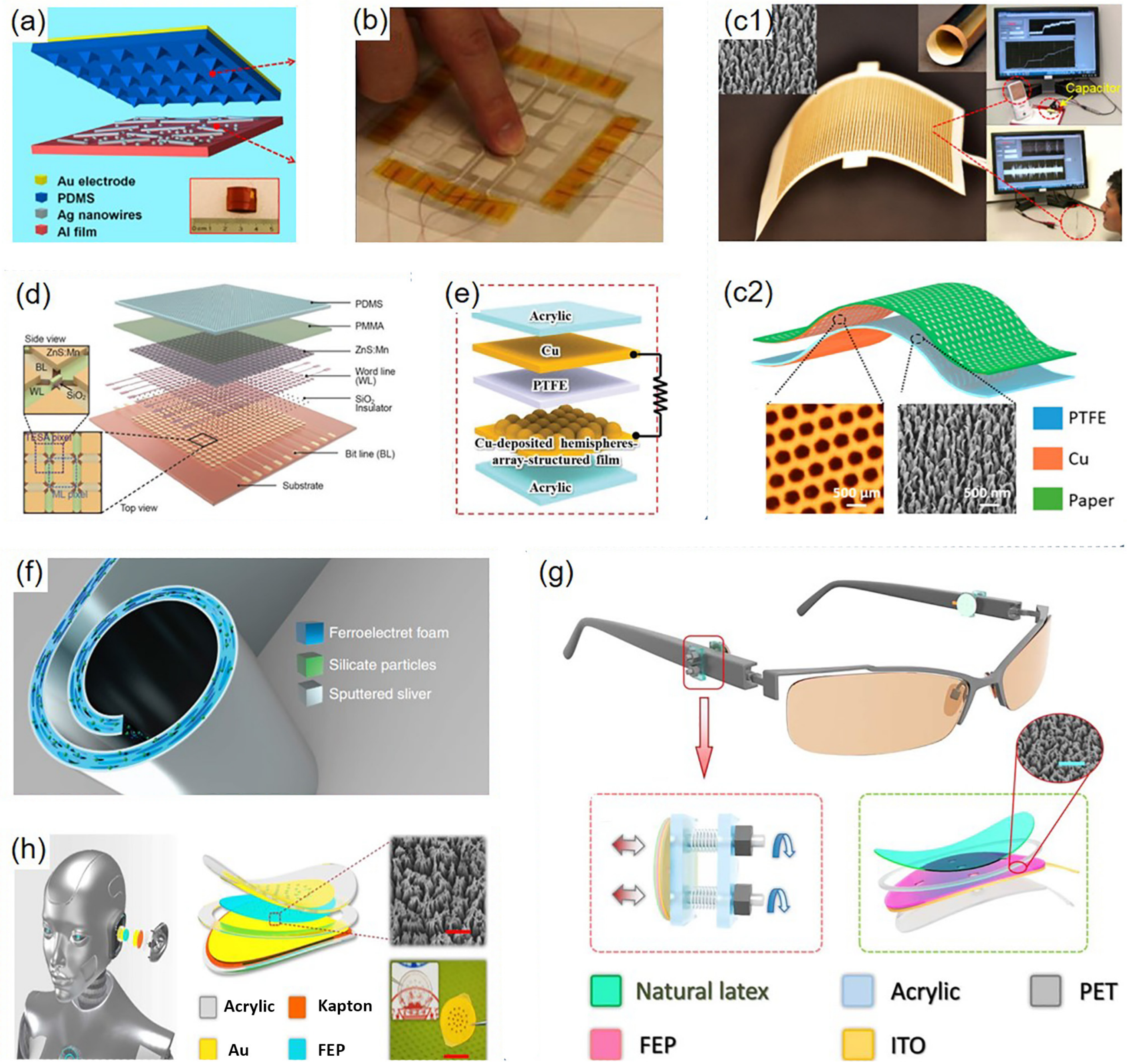


Fig. 6. (Color online) (a) Basic HCI device with contact-separation mode TENG. Reprinted with permission from Ref. [123], Copyright © 2013 American Chemical Society. (b) Basic HCI device with single-electrode mode TENG. Reprinted with permission from Ref. [124], Copyright © 2013 American Chemical Society. (c1) Acoustic energy harvesting device as voice HCI. (c2) Schematic illustrations of the paper-based TENG. Reprinted with permission from Ref. [125], Copyright © 2015 American Chemical Society. (d) Haptic sensing and triboelectric luminescence matrix. Reprinted with permission from Ref. [126], Copyright © 2017 Wiley. (e) HCI device which can be used in harsh environment. Reprinted with permission from Ref. [127], Copyright © 2016 Wiley. (f) TENG-based flexible HCI as both microphone and speaker [128]. (g) Self-powered mechnosensational communication system integrated on glasses. Reprinted with permission from Ref. [129], Copyright © 2017 AAAS. (h) Self-powered sound HCI for robots and hearing aids. Reprinted with permission from Ref. [130], Copyright © 2018 AAAS.

and the gradual marketization of related industries, the research intensity in this field will continue to increase.

3.4. Other TENG-based human-health care related applications

For the three categories of applications described above, the entire system (including commercial devices that may exist) directly interacts with the human body. And the effects on the human body are often immediate, more precisely, can be observed immediately. What this section will show are those applications that are not included in the above categories and provide some environmental and technical support for human-health care. Compared with the first three categories, these TENG human health applications show extremely richness, more diverse technical directions. Therefore, these devices may have an unexpected promotion effect to break the lagging stage of TENG development. Among them, “Disinfection and Sterilization”, “Air Purification” and “Cytology and Biological Applications” are three main aspects. The applications of these aspects are introduced below.

3.4.1. Disinfection and sterilization

Disinfectants are antimicrobial agents that are applied to the surface of non-living objects to destroy microorganisms that are living on the objects (https://www.cdc.gov/oralhealth/infectioncontrol/glossary.htm). Because the technology of disinfection and sterilization has already been mature with diverse existing technologies, there have been early attempts to combine TENG with disinfection. In 2014, Han et al. [141] proposed a ultraviolet (UV) emission device driven by TENG. The device uses the high output-voltage from TENG generate UV rays by inducing plasma discharge. Experiments have shown that after irradiated by the generated UV rays for 30 min, about 98% of *E.coli* can be killed. However, this device also has certain shortcomings, that is, only the contact part emits UV rays. So the suitable scene has received greater restrictions. In response to this limitation, an *ex-situ* UV sterilization TENG device was proposed by Wang et al. [142], as shown in Fig. 7a. The utility of this device could been greatly improved compared to the aforementioned one.

In 2016, Zhao et al. [143] proposed a potential oscillation based underwater disinfectants device, as shown in Fig. 7b. This device uses a rare solid–liquid two-phase form of TENG. The PTFE film has been used as both a single electrode mode triboelectric layer and a waterproof layer to protect the internal ITO and pn junctions from short circuits. When flowing water passes through the surface of PTFE, electrons will be transferred between water and PTFE. As a result, the circular gold foil connected at both ends of the electrode generates potential oscillations, which has the effect of sterilizing and decontaminating. The results show that the output voltages of both electrodes are more than 200 V. Anti-adhesion efficiencies of 99.3%, 99.1%, and 96.0% are achieved for negative-gram bacteria (*Escherichia coli*), positive-gram bacteria (*Staphylococcus aureus*), and diatoms (bacillariophyceze), respectively, on a smooth surface. On the other hand, in general, a humid environment is extremely difficult to have electrostatic effects. Here, the reason why charge transfer can still be achieved in water is related to the excellent triboelectric ability of PTFE. It is reported that negative charges will be generated at the PTFE surface due to contact electrifcation when the PTFE contacts with liquid (e.g., water), and the negative charge layer on the PTFE surface will not dissipate in an extended period of time, even though the TENG has been pulled out of water [24].

In 2019, Ding et al. [144] proposed a low-cost hand-powered water disinfection system, as shown in Fig. 7c. The main disinfection principle adopted by this system is to connect Cu coaxial-electrode to the TENG positive electrode, so that Cu ions are released into the water, which have a disinfection effect. In addition, enhanced electric field increases the permeability of the bacterial cell membrane, and thus enhances the Cu consumption into the bacterial cells. Experiments show that activation efficiency (greater than6-log inactivation of *E.coli*) with only $\approx$200 μg/L Cu ion concentration release, far less than 1.3 mg/L (the maximum contaminant level goal (MCLG) of Cu for drinking water set by the United States Environmental Protection Agency). This application provides a new technical support for the health drinking water in poor areas.

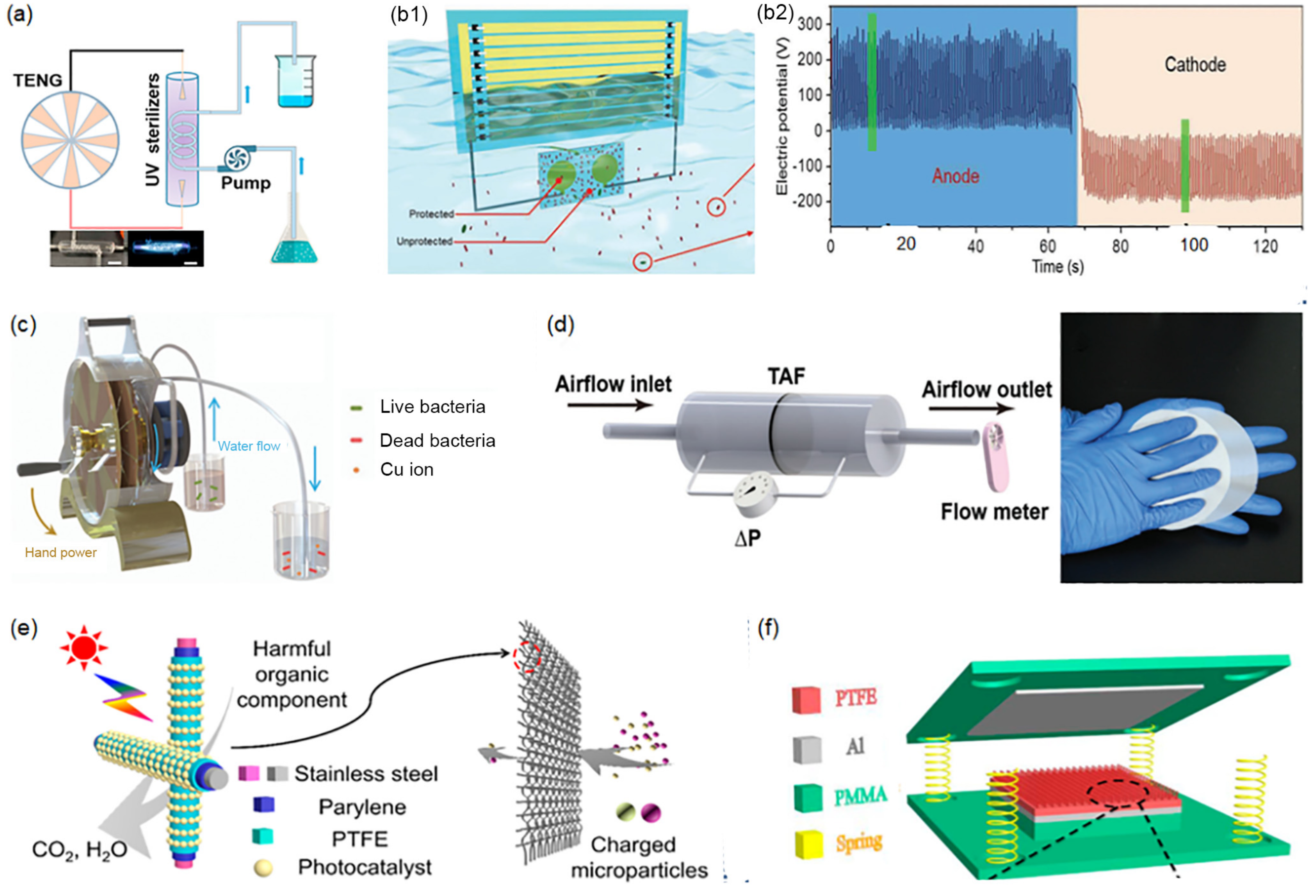


Fig. 7. (Color online) (a) TENG-powered ultraviolet disinfection device. Reprinted with permission from Ref. [141], Copyright © 2015 Elsevier. (b1) Potential oscillation based underwater disinfectants device. (b2) Electric potential measured at the anode and cathode sides of the device at a wave frequency of 1.2 Hz. Reprinted with permission from Ref. [143], Copyright © 2016 Wiley. (c) TENG-powered Cu ions disinfection device. Reprinted with permission from Ref. [144], Copyright © 2019 Wiley. (d) $PM_{2.5}$ filter mask based on electrostatic dust removal triboelectric air flter (TAF). Reprinted with permission from Ref. [145], Copyright © 2018 Wiley. (e) Air filtration device based on electrostatic adsorption effect produced by TENG and the photocatalytic reaction. Reprinted with permission from Ref. [146], Copyright © 2017 American Chemical Society. (f) Self-powered dopamine (DA) detection device. Reprinted with permission from Ref. [147], Copyright © 2015 American Chemical Society.

3.4.2. Air purification

Dust, pollen, pet dander, mold spores, and dust mite feces can act as allergens, triggering allergies in sensitive people. Smoke particles and volatile organic compounds (VOCs) can pose a risk to health. Exposure to various components such as VOCs increases the likelihood of experiencing symptoms of sick building syndrome [148]. Therefore, air purification equipment can also serve human-health care to a certain extent. The most direct way to combine TENG with air purification is electrostatic dust removal. In 2017, Bai et al. [145] proposed a washable $PM_{2.5}$ filter mask, as shown in Fig. 7d. The mask is made of nylon and PTFE. The particles in the air are adsorbed and removed by the electric charge generated from this contact-separation mode TENG. Experiments show that it has a removal effciency of 84.7% for $PM_{0.5}$, 96.0% for $PM_{2.5}$, which are 3.22 and 1.39 times as large as the uncharged one. The realization of this technology can help to improve the respiratory health of the urban population to a certain extent.

Almost at the same time, Feng et al. [146] showed another TENG-based air filtration device (Fig. 7e). In this device, the photocatalyst P25 or Pt/P25 was embedded on the surface of polymer-coated stainless steel-wire network. Therefore, under the combined effect of the electrostatic adsorption effect produced by TENG and the photocatalytic reaction, the degradation of Rhodamine B (RhB) increased over 50% and the degradation of formaldehyde doubled. This technology can also be used for indoor air purification and thus serves to improve the respiratory health of urban populations.

3.4.3. Cytology and biology related applications

TENG also has the potential to be applied in the field of cytology and biology. Although these attempts are still far from being put into production, many studies have verified its feasibility and development value. Especially in recent years, more and more researches in this field, combined with a large number of emerging technologies, will benefit the long-term improvement of human health in the future.

In 2015, Jie et al. [147] developed a self-powered dopamine (DA) detection instrument, as shown in Fig. 7f. With the help of non-stick PTFE and DA's oxidative self-polymerization, high selectivity and sensitivity (detection limit of 0.5 μmol/L, a linear range from 10 μmol/L to 1 mmol/L) have been achieved through the strong interaction between the nonstick PTFE and DA via its oxidative selfpolymerization. This work laid the foundation for the development of portable DA detection devices.

In 2018, Wang and co-workers [149] proposed a new device using TENG to successfully promote wound healing, as shown in Fig. 8a. The ring TENG uses PTFE and Cu foil as triboelectric materials to harvest the kinetic mechanical energy of experimental mice. This energy is directly output to the wound in the form of electrical stimulation, which makes the wound close quickly within 3 d, while normal healing takes 12 d. At the same time, due to TENG's small amount of charge, the safety and comfort of the device are high.

In 2019, Liu et al. [150] proposed a TENG device that can assist cellular drug delivery (Fig. 8b). The device collects the work done by the human body through a freestanding-layer mode TENG composed of PTFE and Cu. TENG generates high voltage pulses, which triggers the increase of plasma membrane potential and membrane permeability. Experiments show that the device achieves efficient delivery of exogenous materials (small molecules, macromolecules, and siRNA) into different types of cells, including hard-to-transfect primary cells, with delivery efficiency up to 90% and cell viability over 94%. Following the Song's work in 2016, the research on drug delivery directions was reopened. However, there are some differences between these two researches: the former is more physically driven, so it can be classified as a TENG-powered implanted device; however, this paper tends to biochemical stimulation, which belongs to the field of cell engineering. So it is classified here. Similarly, Zhao et al. [153] also proposed a TENG-based drug delivery system for accelerating the release of oxorubicin. In the field of drug delivery research, Wu et al. [154] proposed noninvasive iontophoretic transdermal drug delivery (TDD) systems for closed-loop motion detection and therapy.

Lee et al. [155] proposed a device that harvest motion energy for functional electrical stimulation of muscles, which is expected to help treat muscle function loss. In fact, this kind of functional electrical stimulation has great application potential in the field of health care and medical treatment. Not only for muscle stimulation, but also for many other human organs. Then, this team again proposed a TENG-based electrical stimulation device to induce bladder contraction, demonstrating the possibility of functional electrical stimulation for neuromodulation [156]. Zhan group [151] showed another self-powered device that generates functional electrical stimulation, as shown in Fig. 8c. This device can harvest the motion energy and solar energy to generate electrical stimuli that act on the scalp and stimulate brain activity. In the experiment, the device can increase the excitement of mice.

Ogino et al. [157] proposed a new application in the field of coagulation. The research proposed that a PTFE electret tube charged by frictional electricity can prevent the solidifcation of the indwelling catheter in blood vessels. This will provide a research basis for the future development of antithrombotic catheter.

Wang group [152] proposed a device that uses TENG to promote hair growth, as shown in Fig. 8d. The device is capable of stimulating hair growth through a nonpharmacological physical approach. In the experiment, TENG driven by the mouse's head motion continued to generate voltage pulse stimulation to the skin, which made hair growth in this region 1.8 and 2.2 times faster than conventional pharmacological MNX and VD3 treatments. The hair growth rate in this region was 0.73 mm/d (0.41 mm/d for MNX and 0.33 mm/d for VD3). More importantly, the device could overcome the genetic keratin disorder and achieve effective hair regeneration on nude mice. Therefore, this device is expected to provide a new possibility for solving the large problem of hair loss.

In summary, these years' researches have produced some TENG related devices that even not immediate in effect, but can indeed serve human-health care. Starting from several perspectives like daily life and rehabilitation, these researches provide various self-powered technologies that can improve people's health. These results show extremely high levels of diversity. At the same time, they are very close to people's daily lives, their practicality is more obvious. Therefore, it is easier for more people to recognize and understand the contribution that TENG has made to human health improving, which is an impact beyond the devices themselves.

4. Discussion

Although only eight years have passed since the first TENG was proposed, a wide variety of TENG devices with different structures have continuously infiltrated into various branches of scientific research and production. The reason why TENG can be so widely applied in a short period is precisely because it makes up for some of the shortcomings of electromagnetic generators. That is, compared with conventional electromagnetic generators, TENG has the following characteristics: (1) flexible or stretchable devices; (2) low cost; (3) outstanding advantages in low frequency vibration mechanical energy harvest. Therefore, it has broad application prospects in many fields such as the Internet of Things, environmental monitoring, human–computer interaction, self-powered systems, blue energy, human-health care, etc. [158]. Among these various application scenarios, the development of health care, which is most closely connected to humans, will directly affect

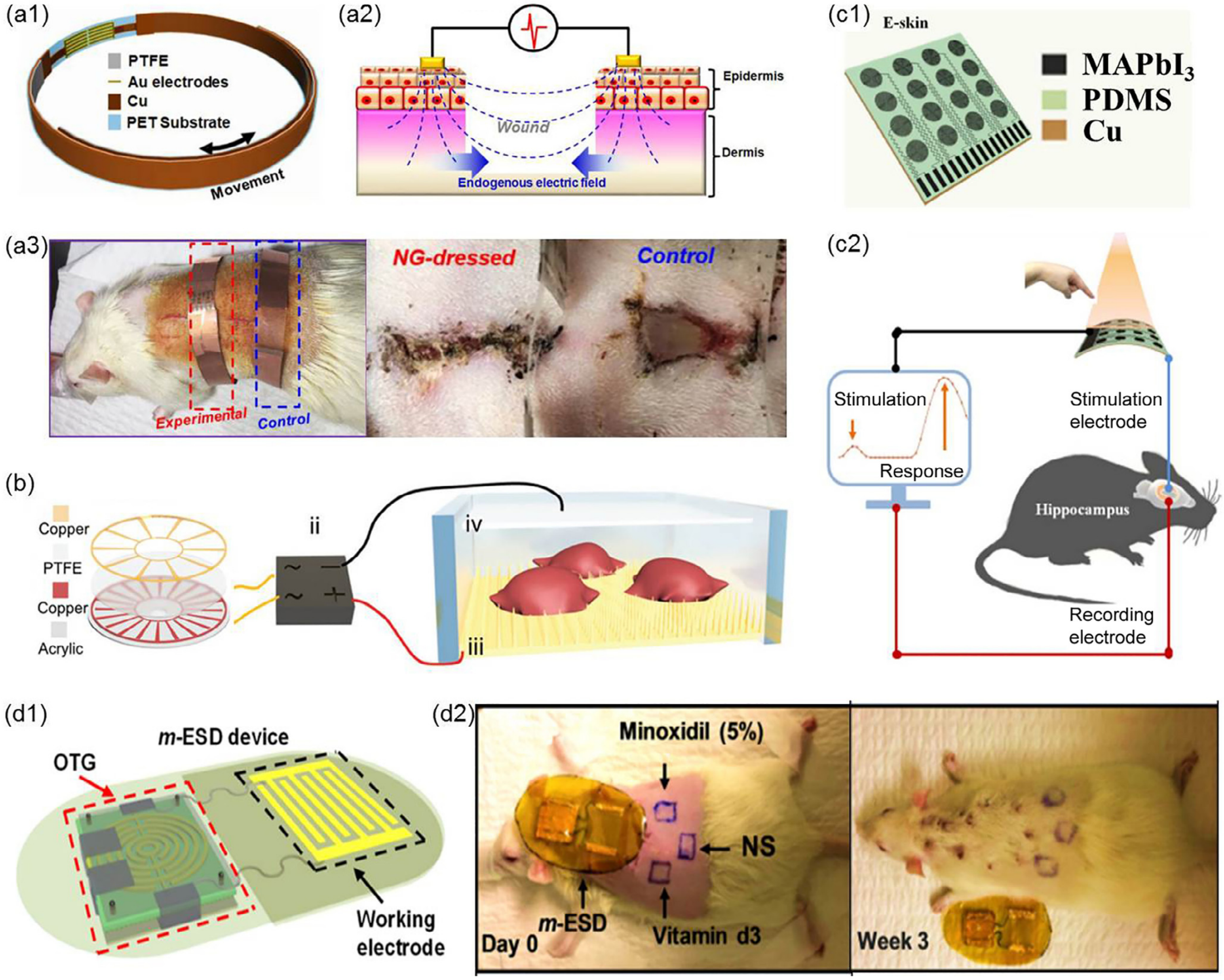


Fig. 8. (Color online) (a1) TENG-base device for promoting wound healing. (a2) Wound-healing mechanism under endogenous electric field. (a3) Images of the experimental setup for TENG-driven linear incisional wound healing. Reprinted with permission from Ref. [149], Copyright © 2018 American Chemical Socity. (b) TENG-based device for cellular drug delivery. Reprinted with permission from Ref. [150], Copyright © 2019 Wiley. (c1) Self-powered device that can generate functional electrical stimulation. (c2) Schematic illustration of the animal experiment. Reprinted with permission from Ref. [151], Copyright © 2019 Elsevier. (d1) TENG-based device, motion-activated and wearable electric stimulation device (m-ESD), which can promote hair growth. (d2) Comparison of hair regeneration under the influence of m-ESD, Minoxidil (MNX), vitamin D3 (VD3), and normal saline (NS). Reprinted with permission from Ref. [152], Copyright © 2019 American Chemical Socity.

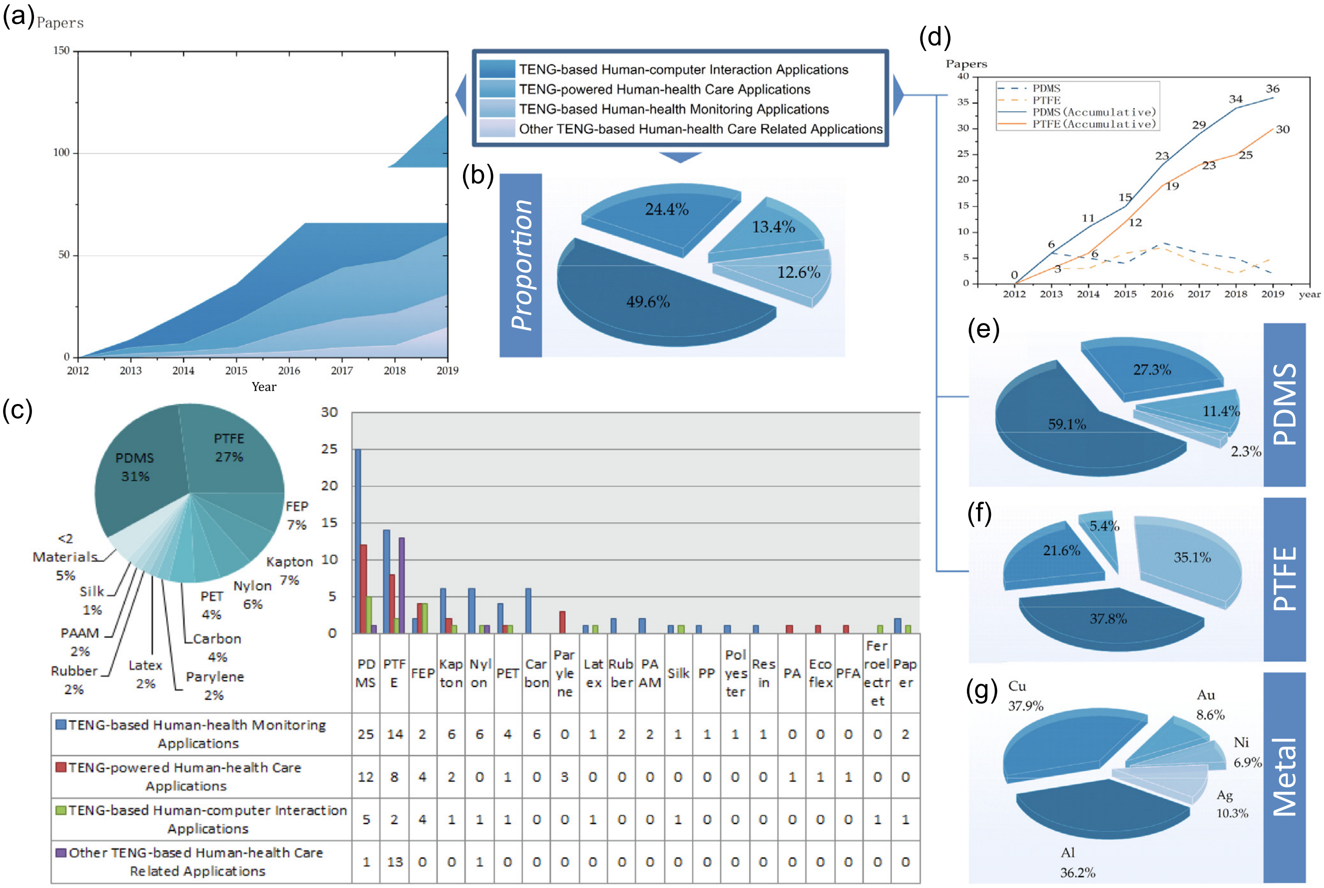
human health and quality of life. The TENG-based health care applications may bring epoch-making changes to modern health care.

In these years of development, many leading teams in the world have made great contributions to the improvement of TENG devices. Numerous researchers have made a large number of attempts to apply TENG for health care and provide valuable and highly referenced cases. After reviewing the previous research works, we have a comprehensive understanding of the development status of TENG in human-health care. However, some of the more in-depth and more data-based analysis and discussions are indispensable. They will more clearly, intuitively and comprehensively summarize and reveal the experience and trends of TENG application in human-health care.

4.1. Development statistics of TENG-based human-health care applications

After sorting out above applications of TENG, it is now necessary to perform data-oriented analysis on these applications. First of all, the statistical scope needs to be declared. (1) Time range: from 2012 to 2019; (2) content range: papers that have practical, inspirational and improving value in the field of health care. As a result, this review includes a total of 112 published papers in this field, including 56 papers in “TENG-based human-health monitoring applications“, 27 papers in “TENG-powered human-health care applications”, 15 papers in “TENG-based human-computer interaction applications” and 14 papers in “other TENG-based human-health care related applications”. The growth curve of papers plotted by year is shown in Fig. 9a.

It can be seen from Fig. 9b that all kinds of TENG applications ushered in a relatively rapid growth in 2016, but eventually slowed down in 2018. The reason for its growth is that after years of accumulation, many key technologies of TENG were initially overcome around 2016, such as the integration of implantable devices, solid–liquid phase triboelectric phenomenon, plasma excitation, etc. All of these at once provided great new development space for the application of TENG, so various researches developed rapidly. After more than two years of development, a large amount of research is close to saturation again. That is the stagnation period for



	PDMS	PTFE	FEP	Kapton	Nylon	PET	Carbon	Parylene	Latex	Rubber	PAAM	Silk	PP	Polyester	Resin	PA	Ecoflex	PFA	Ferroelectret	Paper
🟦 TENG-based Human-health Monitoring Applications	25	14	2	6	6	4	6	0	1	2	2	1	1	1	1	0	0	0	0	2
🟥 TENG-powered Human-health Care Applications	12	8	4	2	0	1	0	3	0	0	0	0	0	0	0	1	1	1	0	0
🟩 TENG-based Human-computer Interaction Applications	5	2	4	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	1	1
🟪 Other TENG-based Human-health Care Related Applications	1	13	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 9. (Color online) (a) The accumulative number of papers from 2012 to 2019 in this review. The growth around 2016 is the fast. (b) The proportion of the four categories of applications. The first category occupies half of the share. (c) Non-metallic materials used as TENG triboelectric materials. Plastic and silicone rubber are two main materials. (d) Annual and accumulative number of PDMS-used and PTFE-used devices. Proportion of (e) PDMS and (f) PTFE used devices in four categories. There is an obvious difference in the fourth category. (g) Proportion of metal materials use for TENG-based health care devices.

overcoming new difficulties. To get rid of such a stagnation situation, from the application level, new fields with more urgent requirements of being self-powered. On the technical level, from the perspective of TENG itself, it is necessary to focus on its structural performance and product level to make it truly have the ability to compete with conventional devices.

Among these four categories of TENG health care applications, “TENG-based Human-health Monitoring Applications” has maintained a relatively stable growth trend from 2012. Most of these applications do not need to combine many interdisciplinary and often non-implantable devices. They have the characteristics of short design cycle, small experimental difficulty, fast results verification and great freedom of improvement. Therefore, it has become the hot spot of TENG in this field and has maintained to nowadays. The starting time of the other three categories of applications became late in turn, reflecting the difficulties of developing or putting these applications into operation to some extent. These difficulties come from the diversification of its technology, which makes its development need to experience slow accumulation of exploration. But on the other hand, this accumulation also provides greater potential for these applications. According to the statistical results, the proportion of the four categories of devices is shown in Fig. 9b. Although the application for health information monitoring still accounts for half of the share, it is declining year by year. The future of TENG is largely converge in the other three categories, which have the hope of leading interdisciplinary exchange and technological innovation.

In recent years, especially in 2019, a large number of applications of the last category have been successively developed. The functions, materials and application modes of the devices are far more abundant than the other three. The development of these devices brings together many traditional or emerging technologies in other fields, revealing the bright prospects of TENG in human-health care applications. And this multi-disciplinary intertwined trend has also come back to confirm that the development of TENG has been recognized by more and more researchers in traditional disciplines in recent years. It will lay the foundation for further in-depth cooperative research in the future, and create possibilities for breaking the current platform period of sluggish development of TENG.

4.2. Statistics of triboelectric materials for TENG-based human-health care devices

4.2.1. Non-metallic triboelectric materials

The triboelectric series of the material plays a decisive role in the output performance of TENG. Therefore, statistical analysis based on the selected triboelectric materials can summarize and reveal some experiences or problems that were initially ignored. As shown in Fig. 9c, the types and quantities of non-metallic materials used as TENG triboelectric materials during the eight years were counted. It should be noted that due to the high degree of similarity of commonly used silicone rubbers, PDMS has a certain representativeness as a typical type of silicone rubber materials.

Therefore, other unspecified silicone rubber materials are also considered as PDMS in statistics. Under this rule, there are still up to 20 non-metallic substances that have been tried for the triboelectric layer. Among them, except for a small amount of special-purpose materials like graphene, most are polymers. Among polymers, plastic materials occupy a large proportion. As an excellent insulator, plastic can easily carry static electricity and maintain it for long. Being at the top of the triboelectric series, plastic has an inherent advantage as a TENG material. As for the silicone rubber materials, due to the high demand for flexibility in the field of human-health care, they have demonstrated its unique superiority, thus also occupying a large number of numbers.

Obviously, in the health care field, the most mainstream materials of TENG are PTFE in plastic series and PDMS in silicone rubber series. In order to further show the development of these two most frequently used materials, Fig. 9d shows the growth curve of the number of papers using these two materials. The earliest developed health information monitoring devices are mostly flexible wearable devices, so PDMS-used devices started relatively earlier than PTFE. On the other hand, with the deepening of research, the superior characteristics of PTFE were gradually recognized by researchers, which led to a rapid growth in PTFE-used devices. PTFE catches up with the previously dominant PDMS and becomes another mainstream material.

On the other hand, according to Fig. 9c, although half of the non-mainstream materials have been tried by researchers, most of them have not been tried again. This shows that these materials must be difficult to meet requirements to some extent. This does not mean that the research of these materials has lost its meaning, but that their superiority has not been well demonstrated in the current application environment. And their fields of expertise are likely to be discovered gradually with the development of technology. Therefore, in the future research, these materials still have the potential as special TENG layers. The best examples are degradable materials such as poly(lactic-*co*-glycolic acid) (PLGA) and polycaprolactone (PCL). TENG with these materials can achieve biodegradation in the body, and the final product is non-toxic and harmless to the human body. This is the irreplaceable feature compared to PDMS and PTFE.

It can be further found that in the emerging TENG-based health care device, the role of PDMS is slowly changing. Compared with acting as triboelectric materials, PDMS has gradually evolved into the most common encapsulation material, becoming an important auxiliary material for integrated implanted devices. By comparing the application fields of PDMS and PTFE, the properties and application differences of these two materials can be more intuitively shown, as shown in Fig. 9e, f. It is not difficult to find that PDMS is widely used in health information monitoring devices, and the applications are more limited. In contrast, the application scenarios of PTFE appear more extensive, especially in the number of HCI applications is significantly higher than PDMS. One of the reasons for this phenomenon is that HCI devices are one of the latest emerging TENG applications in health care. It skipped the exploration period, and naturally adopted PTFE, which is more excellent in output performance and fatigue characteristics. And PDMS correspondingly transformed into an encapsulation material, achieving complementary advantages. From this, we can see that the above-mentioned changes reflect to a certain extent the progress and innovation in TENG-based health care. The evolutionary history of materials has become the epitome of the advancement of TENG technology, which also shows that the combination between TENG and health care is increasing closer. During the research process, many material-attempts have become history, and a few excellent choices have gradually been refined. In the end, today's TENG output performance is greatly improved.

4.2.2. Metal triboelectric materials

Compared with non-metallic materials, metal materials used as both electrodes and triboeletric layers are often ignored. Fig. 9g shows the use of metal materials over the years. Among them, Al foil is the most commonly used, not only because of its excellent electrical conductivity, but also because of its excellent electropositivity in triboelectric series. In addition, Al foil has good stability, easy processing and high cleanliness. It is difficult for microorganisms such as bacteria to grow on its surface. Therefore, Al foil has become the most widely used metal material in health care devices.

As a similar substitute for Al foil, Cu foil sacrifices cleanliness in exchange for better conductivity. Therefore, if used properly, using Cu foil instead of Al foil can increase the output current value.

The important reason why Au foil was also used as a metal triboelectric material is not due to its electropositivity or electrical conductivity (in fact, it is not as good as Al and Cu foils), but due to its excellent ductility. Au foil can be much thinner than other metal materials, so the volume of TENG can be further reduced. In addition, Au foil can be used to some extent due to its high stability. Compared with the former two, it is more difficult to be oxidized, which is conducive to long-term use.

Nickel is the standard partner for parylene. Nickel-titanium alloy has superelasticity and shape memory, which is the most commonly used medical metal material. However, nickel-titanium alloys are prone to corrosion to varying degrees in the body, leading to the precipitation of nickel ions. If nickel ions are released into adjacent tissues or blood, they may cause allergic or toxic reactions, and may even cause leukemia. Parylene is thin, corrosion-resistant, and has good compatibility with human tissues and blood. It acts as both a triboelectric layer and an encapsulation layer, which can effectively provide an inert isolation layer to prevent the nickel ions precipitation. Therefore, parylene makes the application of nickel feasible.

4.3. Discussion on electrode materials for TENG-based human-health care devices

In the foregoing years of development, despite the constant attempts and changes of triboelectric materials, the use of electrode materials is often conservative. Until today, the most commonly used electrodes are still metal materials, such as copper, aluminum and silver. The reason for this situation is largely due to the fact that the conductive properties of metal materials are objectively too excellent, and their various physical and chemical properties are stable and convenient. In addition, coupled with factors such as low cost, wide supply and low processing difficulty, conventional metal electrodes are fully competent and often the best choice in most application scenarios.

On the other hand, with the gradual declining of innovation in conventional application research, devices for special scenarios have become new research choices. These devices often have special requirements on the characteristics of electrode materials. Among them, some materials are actually not new in research, which, in other words, have gradually joined the range of common electrode materials. Such as carbon nanotubes as electrodes to obtain high strength and high flexibility [94,115]. Additionally, carbonacous materials have the advantages of low-cost, abundancy and comparatively good conductivity. For another example, ITO is adopted by many wearable devices due to its outstanding transparency and conductivity [47,90,143]. These researches have been discussed in the previous chapters.

However, it can be found that although carbonacous materials have good flexibility and stretchability, their transparency is insufficient. Although ITO has good transparency, the stretchability is lacking. Therefore, in order to meet the above requirements at the same time, some more complex materials have been tried. As mentioned above, nano-scale metal materials have been developed, the most typical being silver nanowires (AgNWs) [44,52]. AgNWs are normally dispersed in silica gel to become conductive composite materials, which can exhibit comprehensive performance. Also due to the extreme requirements for stretchability and transparency, semi-liquid ionic gels have received widespread attention, such as the aforementioned PAMPS ionogel [49] and PAAm-LiCl hydrogel [59]. However, no material can be perfect. Although semi-liquid ionic gels have excellent performance, once the hydrogel is dehydrated, it will become friable and opaque. In response to this problem, some special ionic conductor electrodes have been proposed. For example, Zhang et al. [159] proposed the ion-conducting elastomer (ICE) electrode. The study shows that ICE-iTENG completely avoids the dehydration or evaporation of liquid solvents, and that ICE is thermally stable up to 335 °C. In addition, the liquid electrodes are selected in few research which are no longer restricted by the shape at all, but its use is relatively primitive. The most cases have used NaCl solution as the liquid electrodes [43,51].

In summary, although the electrode material may have a less significant effect on the performance of TENG than the triboelectric material, choosing a suitable electrode material can often further improve the overall performance of the device. The research on new materials can bring more possibilities for breakthroughs in electrode, and it is also related to the future of TENG's commercialization. Therefore, electrode's development status should never be ignored.

5. Conclusion

Since TENG was first proposed, a lot of researches around the world have made great contributions to the development of TENG. Their multi-domain and multi-level explorations and attempts have guided and accelerated the application of TENG in the field of human-health care, which has also resulted in the extremely rapid growth of TENG-related technologies in this field. All these provide valuable research foundation and practical experience for future research work. On the other hand, the field of health care is one of the earliest application fields combined with TENG. The development status of this field has always represented the forefront of TENG technology, reflecting the entire TENG development history. It is true that after years of development, TENG's related research on health care has gradually transitioned from the exploration stage to the application improvement phase. The applications in this field have also undergone a transition from simple to multiple, and from novel to practical. These changes can be intuitively demonstrated from the change of triboelectric materials: PTFE and PDMS are competitors to each other with different characteristics, but finally have achieved complementarity. In order to achieve new breakthroughs, we must not be attached to existing solutions. It is possible for brand new technologies that should be seriously considered.

On the other hand, to this day, the existing TENG-based health care devices are still far from the replacement of conventional medical devices. There is a long way to go in the extensive and in-depth research in this field. Therefore, TENG should not exist in the science and technology world independently and in isolation. In the period of the next decade or even a century, new research should focus not only on TENG itself, but also on the combination of TENG with other emerging technologies and new materials. This kind of combination attempts would finally achieve a double breakthrough in the theoretical foundation and production application by realizing the complementary advantages of TENG and other technologies. Then, the TENG-based health care applications will become truly universal.

Based on the foregoing discussion, the history and future development of TENG for health care can be summarized as follows:

(1) In the final analysis, the core practicality of TENG is to convert the low-frequency and small motions that were originally dissipated into usable energy (signals). This undoubtedly has a high degree of fit with human-health care applications. TENG will definitely has a place in the future development of this field.

(2) In field of health information monitoring, the applications have developed most rapidly, but at the same time, have the most serious monotonousness. Until now, a large amount of works have focused on the monitoring of pulse, breathing and body motions. Most of them are simply judging the frequency and amplitude of motion by the number of signals and the peak value. The studies of more detailed and in-depth monitoring functions, such as the identification of health and non-health signals, the monitoring of human facial signals and the monitoring of human muscle status, are still in the infancy. In the future, with the shrinking development of conventional TENG monitoring devices, these new directions with broader practical prospects will become the new research hotspots.

(3) In field of TENG-powered health care devices, due to the involvement of energy storage and conversion, the technical difficulty of application is higher than the former. However, as the original function of TENG, it has always been the most research-oriented direction in all application fields. At this stage, in addition to the large-scale motions of the body, the harvest of motion energy from the heart and thorax has also been achieved. Although restricted by the low efficiency of TENG power generation, the feasibility of self-powered health care devices has been verified both from the principle and the experiments. With the further improvement of TENG output performance in the future, including the maturity and optimization of technologies mentioned above (such as charge pumps, current amplification technology, material polarization treatment and switched-capacitor-convertors), more and more conventional devices will have the possibilities to combine with TENG to serve health care. And the implantable devices harvesting the energy of the heart, thorax and muscle will have the most development potential.

(4) In field of HCI, many researches are still in the experimental stage. Most of these attempts are to transfer subjective information to the computer in the form of switching signals. In this process, TENG mostly played the role of a trigger, and did not really solve the identification of signal characteristics. For example, most of the judgment is made only on the presence, absence or timing of sound, rather than matching the sound waveform. The reason is that the output of TENG at this stage is not stable enough and accurately controllable. However, in the future, once the output could have a higher stability, there will be a huge TENG application space in HCI, such as using TENG for human–machine motion tracking and paired speech recognition for the alphabet.

(5) In other TENG-related health care applications, previous work has provided inspiration for the future. To sum up, it is based on the characteristics of high output voltage of TENG and safe for human body that combines the TENG with health care devices. This combination can provide people with more reliable device selection, which is an inherent advantage of TENG devices.

(6) In aspect of device productization, the most urgent problem is the higher integration of the product. It is not difficult to find that many researches only focus on the part of the

device that realizes signal collection or energy harvest, but actually come with extremely large signal transmission and processing systems. Therefore, the integration of health care devices with wireless transmission modules, the integration of energy harvesting devices with energy storage & output modules, and the integration of new technologies with conventional devices are the only paths TENG must become popular and industrial. Another important bottleneck in the realization of productization is the stability and reliability of TENG. In particular, sensing devices have high requirements for signal identification and calibration. The output performance of TENG is often unstable and is affected by many factors, such as temperature, humidity, wear, and material fatigue deformation. In response to the above problems, the current measures are often to combine more reasonable packaging technology and use the superposition of multiple layers of materials to obtain comprehensive properties. But at the same time, the enhancement effect of TENG's form innovation on stability and reliability should not be ignored. It would be meaningful to obtain a TENG with adaptability to temperature and humidity changes, or automatic compensation.

(7) In aspect of materials, TENG's exploration in health care over the years has provided extremely rich experience for the selection of existing commonly used materials. With the clear structure and principle of TENG, the development of conventional TENG has come to the platform stage. Therefore, for the future research, the existing conventional materials will not be the focus of research. Looking for new materials (or material pretreatment technology) with better charge transfer properties, biocompatibility, flexibility, elasticity, ductility, degradability, transparency and lightness, materials (or material processing technology) are the key to breaking through the TENG platform period. Therefore, cutting-edge personnel in the field of material science are urgently required to be able to join this TENG-based field in order to usher in a new era of rapid development of TENG.

(8) After productization, TENG will also face the challenge of commercialization. Commercialization means that it should have the ability to scale profitability. And the basis of scale profitability is the possibility of mass production. However, as demonstrated in (7), in order to pursue TENG's performance or special functions, most devices generally have a series of problems such as difficult processing, complex processes, high environmental requirements and expensive materials. Although these problems will be alleviated with the upgrading of 3D printing technology (such as flexible printing technology, etc.) and the in-depth research of new materials, this process will inevitably be long and require a lot of effort.

Conlfict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Hao Wang, Jia Cheng, and Zhong Lin Wang conceived the idea and guided the review. Hao Wang, Jia Cheng and Linhong Ji carried out the concepts, design, and definition of intellectual content, literature search and manuscript preparation. Zhaozheng Wang provided assist of literature search, manuscript revision and editing. Jia Cheng and Zhong Lin Wang supervised the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2020.10.002.

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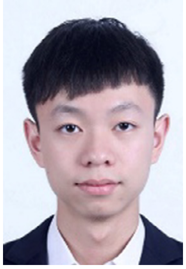

Hao Wang is a M.E. candidate in the research group of Prof. Linhong Ji at the Department of Mechanical Engineering, Tsinghua University, under the supervision of Associate Prof. Jia Cheng. He earned his B.E. degree in Zhejiang University in 2018. His research interest includes theoretical and experimental studies on mechanical energy harvesting by triboelectric nanogenerators and its application to health care and agriculture.

Jia Cheng is an Associate Professor at Department of Mechanical Engineering, Tsinghua University. He earned his B.E. and Ph.D. degrees at Tsinghua University in 2002 and 2008, respectively. His research spans areas including multiphisics feld coupled simulation, optimization design, triboelectric nanogenerator, and rehabilitation engineering.

Zhong Lin Wang received his Ph.D. from Arizona State University in Physics. He now is the Hightower Chair in Materials Science and Engineering, Regents' Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Tech. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic device.