Review
Leveraging triboelectric nanogenerators for bioengineering
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SUMMARY
Triboelectric nanogenerators (TENGs) are able to convert low-frequency biomechanical motions into characteristically high-voltage and low-current electrical signals via a coupling of contact electrification and electrostatic induction. Resulting from a unique working principle, TENGs hold a collection of compelling features, including light weight, structural simplicity, cost-effectiveness, biocompatibility, and a wide range of soft materials choices. Electrical signals generated from human body motions via TENGs could be used as sustainable power sources, active biomonitors, and electrical stimulation therapeutics for bioengineering. Here we comprehensively reviewed the advancements in using TENGs for on-body energy, sensing, and therapeutic applications to build up a body area network (BAN) for personalized health care. We concluded our review with a discussion of the challenges and problems of leveraging triboelectric nanogenerators for bioengineering.

INTRODUCTION
Global concern on health has raised tremendous interest in accessing various physiological status data of the human body via diverse wearable bioelectronics. Continuous and long-term monitoring of the body is preferred since new diseases are always emerging in a sudden manner, including the recent severe acute respiratory syndrome novel coronavirus 2 (SARS-CoV-2). On the one hand, using wearable devices has been becoming a popular lifestyle to access the personal health status anywhere and anytime. On the other hand, with an increasing elderly population, finding practical health care solutions is becoming more challenging than ever. Compared with acute diseases that may be treated intensively in a relatively short amount of time, chronic diseases bring forth many clinical treatment requirements, including the need for long-term health condition monitoring, continuous health data analysis, and even on-demand treatment for personalized health care. Therefore, wearable and implantable biomedical devices are indispensable for modern clinical treatments, including observing, recording, and evaluating all kinds of bioactivities and executing the device’s functions for therapy. Consequently, as the world marches into the era of the Internet of Things (IoT), physicians are becoming more comfortable promoting human well-being through biomedical devices that are widely deployed on the human body for health data collection, analysis, and personalized treatments. To achieve these goals, building a body area network (BAN) consisting of wearable and implantable sensing and therapeutic devices that integrate functionalities of powering, diagnosing, and curing in a closed-loop form is highly desired for personalized health care. These essential features in a BAN system allow biomedical devices to develop favorable characteristics such as self-sufficiency, system-level multi-functionalities integration, reliability, biocompatibility, biodegradability, low power consumption, and even self-powering capability.1–4 However,
before these features evolve to maturity, challenges exist for the broad applications of biomedical devices that are integrated with features of sensors,\textsuperscript{5,14} power sources,\textsuperscript{3,20} and therapeutics in a BAN system for personalized health care.\textsuperscript{21,29}

The popularization and mass implementation of biomedical devices for customized applications in the foreseeable future set a critical prerequisite: a sustainable and reliable power supply is necessary for wearable and implantable sensing and therapy. However, the traditional centralized power supply system is limited, as it cannot efficiently provide a pervasive energy solution for distributed biomedical devices throughout the human body. Batteries are readily available and seemingly provide us an answer to the need of power sources for biomedical devices. However, issues with batteries, including unfavorable lifetime, toxic chemicals, and bulk volume, impede their potential widespread deployment in biomedical devices.\textsuperscript{30} Especially for in vivo application, excessive heat generation from batteries is detrimental. In addition, secondary surgery is usually required to replace batteries for implantable devices, which exerts physical injuries and emotional distress for patients. Due to the drawbacks of batteries and the high demand for a suitable power source for biomedical devices, the industry is pushing for the advancement of self-powering technology that can exploit ambient energies around the human body and generate electricity to drive biomedical devices for sensing and therapy sustainably.\textsuperscript{31-34}

Much research sheds light on different strategies to generate electricity by exploiting various forms of body-related energies, such as biomechanical,\textsuperscript{31,35} chemical,\textsuperscript{36} and thermal energies,\textsuperscript{37} etc. Accordingly, many materials have been developed that are responsive to these energies.\textsuperscript{38-40} Particularly, since low-to-medium-frequency biomechanical motions are abundant around the human body, the approach using triboelectric nanogenerators (TENGs) is the most popular and widely investigated route for biomechanical energy conversion.\textsuperscript{41-46} TENG, an emerging electricity generation platform first reported in 2012,\textsuperscript{47} has attracted research efforts from various aspects, including device fabrication, property enhancement, mechanism investigation, and on-body applications, due to their simple structure, cost-effectiveness, and reliable performance.\textsuperscript{5,15,16,18,21,48-59} Electricity generation from various kinds of biomechanical motions are demonstrated using TENGs, including walking,\textsuperscript{48,53,60-63} arm shaking,\textsuperscript{13,33,48-51,64,65} breathing,\textsuperscript{5,16,18,65} heart beating,\textsuperscript{54,55,66,67} pulse wave,\textsuperscript{68-72} vocal vibration,\textsuperscript{71,73-75} blood flow,\textsuperscript{54,67,70} pressure from blood vessels,\textsuperscript{56} stomach peristalsis,\textsuperscript{76} etc. Such readily attractive features, along with current advancements of TENGs, have facilitated the rapid development of wearable and implantable TENGs as bioelectronics for all kinds of applications, including reliable power sources for biomedical devices,\textsuperscript{77-85} sensitive sensors for physiological activity detection,\textsuperscript{86-88} and electrical stimulation for therapeutics.\textsuperscript{89} To date, many examples have been demonstrated using wearable and implantable TENGs to power an electronic watch,\textsuperscript{90} light-emitting diode (LED) arrays,\textsuperscript{80} and pacemaker\textsuperscript{16,55} to monitor limb motion,\textsuperscript{9,91} heart rate and pulse wave,\textsuperscript{59,71} and to promote hair regeneration,\textsuperscript{26} wound recovery,\textsuperscript{15,24,92} bone healing,\textsuperscript{23,65} etc. Nevertheless, using TENGs as biomedical devices for practical clinical applications toward personalized health care in a BAN system has met with great challenges.

The characteristics of wearable TENGs, including their wearability, durability, stability, electricity output manipulation, and system design, require further studies. For instance, research on fabric-like wearable TENGs is flourishing because fabrics are readily woven into clothing.\textsuperscript{12,27,50,77} However, during wearing, abrasion issues impede the seamless integration of fabric-like wearable TENGs with traditional clothes.
Parameters, including environmental factors (e.g., humidity, temperature fluctuation), complex human body micro-environments (e.g., sweating), laundry-induced performance degradation, etc., are still under investigations. For implantable TENGs, biosafety, biodegradability, miniaturization, tissue-device integration, etc., are also challenging issues. Currently, three main functionalities of wearable and implantable TENGs have been intensively studied: (1) sensing physiological information for bio-monitoring and diagnostic purposes, (2) providing electrical stimulation for therapeutics, and (3) acting as a sustainable energy source for sensing and therapeutic devices. These three roles are less systematically addressed in the literature to build a self-powered, autonomous BAN for closed-loop sensing and therapeutic applications. Most studies focus on one or two of these three aspects, for instance, self-powered (energy) heart rate monitoring (sensing), self-powered (energy) pacemaker (therapy), undractive bladder monitoring (sensing), etc.

In addition, the information flow pathway between these devices is indispensable for achieving an autonomous BAN system. For example, the post-processed information of physiological signal data from self-powered TENG sensors (e.g., heart rate) helps guide the corresponding therapeutic TENGs to exert their specific functions efficiently, accurately, and promptly (e.g., activate the pacemaker if an emergency happens to a patient). Developing an autonomous, closed-loop BAN system is critical, ranging from energy provision to sensing and therapeutic capabilities by leveraging biomechanical motions around the human body via wearable and implantable TENGs. This development is essential, and prospects for personalized health care appear promising as this field continues to evolve.

In this review, wearable and implantable TENGs for electricity generation from body-associated biomechanical energy and their bioengineering applications as power sources, sensing, and therapeutic devices are highlighted (Figure 1). First, electricity generation from various biomechanical motions using wearable and implantable TENGs for powering biomedical devices is summarized. Then, applications of TENGs for self-powered biomedical sensing and electrical stimulation therapeutics are fairly discussed. Furthermore, insights into constructing an autonomous BAN system are also highlighted. Finally, conclusions and perspectives on current challenges and future research directions are proposed. This review functions as a rundown of the full-scale description of electricity generation from body-associated biomechanical energy via wearable and implantable TENGs toward personalized health care in the era of IoT.

**ENERGY**

Daily activities of the body are ubiquitously associated with various kinds of motions, which can be converted into electricity using wearable and implantable TENGs for various applications (i.e., powering bioelectronics). According to the features of these biomechanical motions, such as the location, intensity, and frequency, TENGs can be either directly attached to or worn on the human body. In this section, wearable and implantable TENGs as potential power sources for bioelectronics are systemically discussed. The four working modes of TENGs, including vertical contact-separation (CS) mode, lateral sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FS) mode, are also briefly mentioned.

**Wearable TENGs as sustainable power sources**

**Foot and leg motions**

Foot striking is estimated as an incredibly rich energy source with 67 W of potential power from a brisk walker. Various TENGs have been actively investigated for
footfall energy conversion. Since footfall usually holds a force directed toward the ground, TENGs utilizing the CS mode are widely applied for this motion energy conversion. Notably, the multilayered structure attracts attentions for its effectiveness in enhancing the output performance. In 2013, Bai et al. demonstrated an integrated multilayered TENG with a small size (3.8 cm x 3.8 cm x 0.95 cm), and lightweight (7 g) for electricity generation from regular walking. The structural design provides a simple method for stacking multiple TENGs without expanding the area or considerably complicating the fabrication process. It reached a short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) of 660 mA and 215 V, respectively. Later on, Zhu et al. applied a similar idea to build a power-generating shoe insole (located inside shoes) with built-in flexible TENGs. During walking, the footfall pressure generated a maximum V_{OC} of 220 V and a I_{SC} of 600 mA, which was demonstrated to power commercial LEDs and charge a battery. Subsequently, other types of TENG-based insoles and shoe pads (located outside of shoes) were also developed to generate electricity from footfall. Particularly, the high output voltage and decent output current are uniquely attractive to be used as power supply for both wearable and implantable biomedical devices because of the self-sustainable capability.

To make the TENGs efficient for electricity generation during walking, several parameters need to be further optimized, including (1) wearing comfort; (2) high electrical output; and (3) mechanical durability. In the past few years, advances regarding...
Figure 2. Wearable TENGs for sustainable power sources

(A) Charging LIB by jogging with a tube-like textile TENG acting as a shoe pad. Inset shows the shoe pad and the sketch structure of the tube-like TENG. Reprinted from Wang et al. CC BY 4.0.

(B) Current output from a TENG using porous nanocomposite (PNC)-based insole for footfall energy conversion. Reprinted with permission from Fan et al. Copyright 2017, John Wiley and Sons.

(C) Short-circuit current ($I_{SC}$) from walking using the rigid grating-structured freestanding TENG. Inset shows the TENG worn on the leg. Reprinted with permission from Xie et al. Copyright 2014, John Wiley and Sons.

(D) Current output from wearing fabric TENGs on different body parts, including the hand, foot, knee, and elbow. Reprinted with permission from Zhang et al. Copyright 2018, American Chemical Society.

(E and F) (E) Fabric TENG as an elbow patch (left) and the corresponding voltage output (right) from elbow bending. Scale bar, 5 cm. (F) Fabric TENG embroidered on the side of a polo shirt (left) and the voltage output (right) from arm rubbing while walking. Scale bar, 5 cm. Reprinted with permission from Sala de Medeiros et al. Copyright 2019, John Wiley and Sons.

(G) Bracelet-like TENG worn on the wrist to drive several LEDs with arm shaking. Scale bar, 4 cm. Reprinted with permission from Yang et al. Copyright 2018, American Chemical Society.
these aspects have been witnessed. For example, Wang et al. developed a wearable and sustainable power source via a tube-like textile TENG design as a shoe pad (Figure 2A bottom inset) with a rationally designed helix-belt contact structure. The shoe pad was flexible, stretchable, weavable, lightweight, low cost, and waterproof. The authors found that two aspects of the TENG-based pad are critical, i.e., the rational structural design and the right usage of triboelectric materials. Highly conductive carbon nanotubes and carbon black were selected to fill the silicone rubber. These rubber composites were used as both inner and outer electrodes, which are highly conductive (4.3 S m$^{-1}$) and mechanically stretchable (strain at break 620%). Such a combination of a helix-belt structure and a rubber-based soft material endows the triboelectric layers with high contact intimacy, thus achieving highly effective contact between two triboelectric surfaces to guarantee charge density enhancement. As a result, the charge density obtained was 250 μC m$^{-2}$, which was among one of the highest values reported in 2016. The tube-like TENG generated electricity from solely walking and jogging (Figure 2A the top inset), which immediately and sustainably powered an electronic watch and charged the lithium-ion battery simultaneously (Figure 2A). Yi et al. also demonstrated a similar shoe pad to light up LEDs solely with footfall during walking. Such competitive electricity generation capability is very promising to sustainably drive the biomedical devices for personalized health care such as pulse wave sensors in the future without reliance on external batteries. As the shoe pad was constantly in contact with the rough ground during walking, mechanical stability issues may arise since the rubber-based conductive electrode is soft and susceptible to abrasions.

As an alternative to shoe pads, insoles are even more suitable for direct wearing. However, they require more features such as compressibility so that users will not experience any discomfort during walking. For instance, Fan et al. adopted an insole-shaped TENG using a flexible porous nanocomposite (PNC) for striking energy conversion. The PNC with a foam-like structure is a hybrid of a multiwalled carbon nanotube (CNT) network and a polydimethylsiloxane (PDMS) matrix. Each pore within the PNC is a micro-scaled TENG unit. The authors demonstrated that PNC-based TENG insoles were able to convert striking energy to electricity from different foot motions, including bending, stomping, and regular walking, as plotted in Figure 2B. With a thickness of 5 mm and excellent flexibility (barely changing the wearer’s normal gait), such an insole can generate a 170 nA current when bending and even higher current amplitudes when stomping and walking. Nevertheless, the inferior output current may pose issues if such an electricity generator is designed to potentially supply power for biomedical devices. More efforts are needed to optimize the output performance since the current is still in the low range of nano amperes.
Although soft/compressible/stretchable TENGs are among the most popular candidates for achieving biomechanical-to-electrical conversion, TENGs with a rigid structure are also reported as wearable devices with decent electricity output performance from leg motions during walking.\textsuperscript{13,97,114} For example, Xie et al.\textsuperscript{97} designed a TENG composed of a freestanding triboelectric layer with grating segments and two stationary electrodes where components are only allowed lateral sliding movement. Although the whole device was not relatively soft, periodic electrical outputs were generated by exploiting the walking motion when connected to human legs (Figure 2C). Nevertheless, this device was lack of wearability even though it delivered a $V_{OC}$ of $\sim 135$ V and a short-circuit current density ($J_{SC}$) of $\sim 9$ mA/m$^2$ with a high total conversion efficiency of 85% at low operation frequencies. In later studies, knee crouching during the bending of the leg while walking had also demonstrated electricity generation using flexible TENGs.\textsuperscript{7,13,96} Knee crouching requires both mechanical extension and bending. Therefore, features of flexibility and bendability for TENGs are required. To address it, Zhang et al.\textsuperscript{96} developed a fabric TENG that can be directly and comfortably worn on the knee joint. This fabric-based TENG was composed of a Cu (copper)-doped thermoplastic elastomer (TPE) film and nylon fabric (as triboelectric material) that were attached to a polyester (PET) fabric substrate. Such a device can generate electricity from knee crouching, reaching an output voltage and current of 75 V and 6 $\mu$A, respectively. It is also responsive to other types of human motions according to corresponding movement intensity (Figure 2D), such as hand tapping (15 $\mu$A, 350 V), foot stepping (22 $\mu$A, 480 V), and elbow bending (4 $\mu$A, 65 V). All output currents are in the range of micro amperes, which is feasible for most of low-power consumption bioelectronics such as sensors for heart rate monitoring and diagnosis.

**Arm motion**

Swinging of the arm is a ubiquitous motion that can be converted to electricity using fabric-based TENG with separated two layers on the inner forearm and waist in LS mode.\textsuperscript{33,64,65,96} Daily usage, along with continuous washing and other mechanical frictions (e.g., wearing abrasions), could lead to performance deteriorations. Therefore, characteristics such as being waterproof are desired for these TENGs in practical applications. With that in mind, Sala de Medeiros et al.\textsuperscript{33} found that merely spraying a fluoroalkylated organosilane on a piece of fabric was able to induce an excellent water-repelling property, resulting in a very high static contact angle with water (155°). The TENG fabrication process consisted of applying this omniphobic fabric and networked Ag electrode. The TENG was then patched to the elbow area on the sleeve (Figure 2E left), and it generated a voltage of $\sim 5.8$ V (Figure 2E right) from elbow bending. In addition, for aesthetics, this fabric TENG can also be embroidered on clothes as a decoration for shirts, as shown in Figure 2F (left), and simultaneously generate electricity ($\sim 20$ V) when arms come into rubbing contact with its surface (Figure 2F right). Since fabrics and textiles are fundamental building blocks for clothing, fabric TENGs, with various post-treatments to augment functionality, are the ideal forms for developing wearable TENGs to convert biomechanical motions to electricity.\textsuperscript{12,13,50,64,115} For instance, Dudem et al.\textsuperscript{35} designed a fabric TENG using polyaniline (PANI)-coated worn-out cotton textile (PANI@WCT) as the positive triboelectric material and electrode. This fabric TENG was able to induce a charge flow when it was in contact with different materials. The authors demonstrated that an output voltage and current of $\sim 40$ V and 2.2 $\mu$A were obtained when an arm wrapped with a Teflon sheet rubbed against this fabric TENG located under the arm. Nevertheless, only the Teflon sheet was demonstrated by the authors to achieve decent electricity output. Other fabric materials instead of nonporous sheets are preferred regarding the wearing comfort for the whole device.
Besides fabric TENGs, a bracelet-like TENG has also been reported to exploit arm shaking motions when worn on the tester’s wrist. Usually, this type of TENG is highly flexible and even stretchable.\textsuperscript{13,56,91,98} For instance, Yang et al.\textsuperscript{98} injected liquid metal (LM, Galinstan) into a silicone rubber tube, creating an SE LM-TENG that is exceptionally stretchable and applicable for a wide range of body motion energy conversion. When wearing it as a bracelet (Figure 2G), the TENG’s output can reach a maximum voltage, current, and charge density of 64 V, 1.5 $\mu$A, and 21 nC, respectively. A similar idea was also explored by Yi et al.,\textsuperscript{91} who designed a shape-adaptive bracelet-like TENG with a conductive liquid (sodium chloride solution or water) electrode and an elastic polymer cover (silicone). Only taking advantage of arm shaking, the bracelet-like TENG was able to drive more than 80 LEDs, attesting to its effectiveness as a wearable power source. Potentially, by optimizing the device structure and output performance, TENG-based electricity generation from arm motions is a promising energy source to drive bioelectronics.

**Hand movement**

Multilayered and 3D fabric TENGs have been reported for hand motion to electricity generation.\textsuperscript{13,32,64} For example, using polyester fabrics as substrates, Xiong et al.\textsuperscript{13} developed a polyethylene terephthalate (PET) textile TENG with a three-layer structure, as depicted in Figure 2H. The three layers included an HBP (HCOENPs/black phosphorus/PET) fabric that was made by successively coating black phosphorus and hydrophobic cellulose oleoyl ester nanoparticles (HCOENPs) on a PET textile, an electrode fabric that was coated with silver flakes and polydimethylsiloxane (Ag flake/PDMS), and a waterproof fabric that was coated with HCOENPs. As a result, this sandwiched textile TENG exhibited excellent washability (severe washing for 72 hr), deformability (100% tensile strain), and comparable air permeability (1068 L·m$^{-2}$·s$^{-1}$). The multilayered textile TENG can comfortably fit different body regions, as seen in the inset of Figure 2I, showing that it can directly be mounted onto the skin or worn on different parts of the body. With a dimension of $7 \times 7$ cm$^2$, this fabric TENG shows decent output performance when applying a 5 N touching force at 6 Hz with just a hand, generating a voltage of 860 V and a current density of 1.1 $\mu$A·cm$^{-2}$. As plotted in Figure 2I, stable output voltages from different body locations can be produced upon hand touching. Such a high output current is very promising as a power source for biomedical devices with electrical stimulation functions where a relatively high electric field is needed. One thing worth noting here is the competitive features of washability, deformability, and permeability. The thickness of such multilayered textile TENG is also of importance in terms of wearing comfort in different seasons all around the year.

Glove is another attractive candidate due to its proven wearability. For example, Wu et al.\textsuperscript{12} presented a smart e-textile that was based on commercial textiles using a simple solution coating process with silver nanowire/graphene. This e-textile showed a stable conductivity of $\sim$20 $\Omega$·sq$^{-1}$ and can be configured into wearable electricity-generating textiles such as gloves. The authors found that the output, stimulated by fingers’ movements, generated a current that was larger than 2 $\mu$A and a voltage of more than 4 mV, reaching an output performance of 7 nW·cm$^{-2}$. Although performance is still low (especially the output voltage), the simple fabrication method using a scalable, environmentally friendly, full-solution coating process holds great promise for a wide range of other materials.

Chen et al.\textsuperscript{109} reported a further modification to the glove fabrication that utilized traditional woven craft for TENG fabrication with large-scale manufacturing potentials. They designed a self-powered textile TENG based on the freestanding working
mode (FS-TENG). Figure 2J shows the electrode and sliding textile, which can be readily stitched into a clothing, such as typical gloves (Figure 2K), for electricity generation. When rubbing or patting hands, the FS-TENG glove’s generated electricity could light up 18 blue LEDs with maximum current, voltage, and transferred charge of 1.5 mA, 118 V, and 48 nC, respectively. In addition, around 80% of the output voltage remained after the 15,000-cycle test for this FS-TENG glove, indicating decent durability for long-term applications. This is especially critical, as a power source for bioelectronics since stable and continuous output of therapeutic devices is usually required to deliver the satisfied treatment effects. One point which may attract interest is how to integrate both the electrode and sliding textiles together so that the application of electricity generation textile could be expanded to other biomechanical motions.

Various types of patches and on-skin TENGs have also been adopted and investigated for electricity generation for the fingers.12,109,116,117 Since contact materials are critical for the output performance of on-skin TENGs, self-cleaning is a preferred feature, as contaminations (unavoidable for sticky devices) would degrade the performance. To achieve this, Lee et al.110 reported a transparent and attachable TENG unit, which possessed poor adhesive quality with other contact surfaces (namely, anti-contamination and self-cleanable). The anti-sticking effect is realized by functionalization with (heptadecafluoro-1,1,2,2-tetrahydrodecyl) trichlorosilane (HDFS), guaranteeing that the contact surface, which could otherwise become contaminated, is clean (Figure 2L). This design parameter is essential since one cannot avoid touching various surfaces of different materials when wearing this on-skin TENG, which may introduce contaminations that degrade performance. The authors also explored electricity generation applications by converting energy from finger touches on various objects, including fabric and the skin directly (Figure 2M).

Stretchability and a conformal fitting are critical features for this type of on-skin TENGs. For instance, Chen et al.116 used crumpled graphene layers and silicon films to fabricate small TENGs that were highly stretchable and suitable as a patch for finger joint motion mounting. During finger moving, the electrical signal acted as a suitable monitoring parameter for the bending angle. However, it failed to work as a power source for bioelectronics because the output voltage was only ~70 mV. Later on, on-skin TENGs with conformal-fitting capability have been broadly reported as power sources for achieving better wearability.8–11,110,113,118,119 For instance, Liu et al.8 developed a soft hydrogel-elastomer hybrid for biomechanical energy conversion. This ultrathin (~380 μm), stretchable (more than 700%), and transparent (90%) TENG can conform to human skin such as fingers (Figure 2N). It showed no mechanical fatigue or electrical output degradation under 75% strain for 600 cycles (Figure 2O). Such a hydrogel-elastomer hybrid holds the potential for applications as an energy-harvesting skin unit in the near future. Furthermore, Chen et al.111 proposed an elastic TENG by smearing carbon/silicon grease on the dielectric elastomers’ surface. When attached to the back of a hand, it can deform along with the skin moving, as shown in Figure 2P, without disturbing skins’ movements. Although the electricity generation of these on-skin TENGs is still low, the electrical signals are suitable as indicators for various physiological activity monitoring via a self-powered manner.

Muscle stretching

For some applications (i.e., indoor activities) where body motions are limited, direct on-skin TENGs would be preferred. Every motion associated with the body is due to the contraction and relaxation of muscles beneath our skin. The cyclic muscle
contraction/relaxation process can also be directly employed to generate electricity using on-skin TENGs. For example, when one is bending their arm to various angles, the bracelet-like TENG that is placed on the upper arm, developed by Yi et al., displays various electrical signals, as shown in Figure 2Q. Although the output current is limited for direct electricity use, it can be correlated to muscle contraction/relaxation intensity, serving as a suitable self-powered bioelectronic sensor for body motion detection. Generally, most of such on-skin TENGs are used as an artificial skin layer that is designed to detect the external mechanical stimulus. The generated electric signals are useful as inputs to achieve a self-powered human-machine interface. A similar idea was demonstrated by Pu et al., who converted the eye muscle motion into an electric signal. By taking advantage of this electric signal, the motion pattern of eye blinking can be recorded. Thus, using a pre-coding algorithm, they further demonstrated a self-powered, hands-free typing system without the reliance on an external power supply. Thus, for these motions where electricity generation capability is low in terms of output performance, the converted electrical signals themselves can be deployed as sensing data for bioactivity monitoring via a self-powered manner.

**Implantable TENGs as sustainable power sources**

**Respiration**

Breathing, including inhaling and exhaling, is the unconscious physiological activity associated with aerobic creatures. It is a cyclic action that is assisted by various muscular contraction, relaxation, and organ movements. As investigated by researchers, these motions are effective biomechanical energy resources for electricity generation using implantable TENGs. For instance, in 2014, Zheng et al. developed an implantable TENG as a direct power source to drive a cardiac pacemaker in vivo by generating electricity from the periodic breathing motion of the animal thorax. This implantable TENG was composed of two triboelectric contact materials that were PDMS (with patterned pyramid arrays) and aluminum foil (with nano-surface modification), as structurally illustrated in Figure 3A (top). The nano-surface functionalization ensured a robust output performance for its in vivo application. The final implantable TENG had an effective contact area of 0.8 × 0.8 cm² with a frame size of 1.2 × 1.2 cm² (Figure 3A bottom), which was dimensionally suitable for implantation in a small animal such as Sprague Dawley (SD) rat. Figure 3B shows the implanted location between the diaphragm and the liver in an SD rat. During breathing, the inhaling and exhaling of the SD rat caused expansion and contraction of the primary muscle for respiration. This contraction, in turn, made the PDMS and Al foil contact and separate from each other, generating a voltage, current, and power density of about 3.73 V, 0.14 μA, and 8.44 mW·m⁻², respectively. The performance can be further enhanced by merely enlarging the size of the implantable TENG, reaching a higher current output of 0.6 μA with a size of 3 × 2 cm² (Figure 3C). In addition, the authors demonstrated the direct use of the electricity to power a pacemaker in vivo to regulate heartbeat rhythm, as schematically configured in Figure 3D. This feature of being self-sustainable for in vivo devices can not only lower the cost for implantable power sources but also reduce both repetitive surgeries and accompanying suffering that patients must endure. Nevertheless, challenges still exist for implantable TENGs: efficient hermetic packaging is needed to keep the device separate from surrounding biofluid, especially for materials in triboelectric devices with uneven surfaces. Thus, proper encapsulation strategies are required.

**Heart beating**

The beating of the heart is a continuous activity that draws great attentions to in vivo energy scavenging. For instance, in 2018, Liu et al. developed a novel
Figure 3. Implantable TENGs for sustainable power sources

(A–D) (A) Multilayered structure of the implantable TENG (top) and the actual sample with small size held by human hand (bottom). (B) Attaching the implantable TENG (3 cm × 2 cm) to a live rat’s diaphragm (the primary muscle for respiration). (C) Current output of the implantable TENG in (B) due to the expansion and contraction of the rat’s diaphragm movement. (D) Configuration of the self-powered pacemaker using energy from this implantable TENG. Reprinted with permission from Zheng et al.16 Copyright 2014, John Wiley and Sons.

(E–G) (E) Illustration of the self-powered endocardial pressure sensor (SEPS) (top) and the photograph of SEPS in bending and original states. Scale bar, 0.5 cm. (F) Diagram of the semaphore acquisition from the SEPS implanted into an adult Yorkshire swine’s heart. (G) Comparing signals using electrocardiography (ECG), femoral arterial pressure (FAP), and SEPS under different physical statuses, including resting, arousing, and active. Reprinted with permission from Liu et al.54 Copyright 2019, John Wiley and Sons.

(H–J) (H) Illustration of the implantable body-integrated self-powered system (BISS) and the photograph of LED bulbs lit up by implanting the BISS in a rabbit. (I) Generated voltage and current of the BISS when the rat moved up and down. (J) Charging a capacitor using the BISS. Reprinted with permission from Shi et al.56 Copyright 2019, American Chemical Society.
implantable TENG for a self-powered endocardial pressure sensor (SEPS). The sensor is able to convert energy associated with blood flow within the chambers of the heart into electricity. The implantable TENG was flexible (Figure 3E bottom) and exhibited a layered structure, as illustrated in Figure 3E (top). It is worth pointing out that the authors applied two encapsulation layers, the first being a PTFE film (50 µm) and the second being PDMS, due to its advantageous biocompatibility and blood compatibility for better leakage protection. When implanted into the left ventricle (LV) of a swine’s heart (Figure 3F), this implantable TENG-based SEPS was successfully employed as a sensor for real-time endocardial pressure (EP) monitoring with self-powering capability. The SEPS converts the cardiac contraction and relaxation, associated with periodic changes in ventricular pressure, into electrical signals, which carry abundant information about physiological parameters. The signals of electrocardiography (ECG), femoral arterial pressure (FAP), and the SEPS ($V_{LV}$) were detected and compared with each other (Figure 3G). A positive $V_{LV}$ of $\approx 80$ mV was obtained at resting status, and both FAP and $V_{LV}$ remained constant, indicating little interruption of the implanted SEPS on cardiac functionality. After the epinephrine injection (namely, enhancing cardiac contractility and thus EP), the peak $V_{LV}$ was increased to $\approx 250$ mV simultaneously with the elevation of FAP. Detailed features of both SEPS and FAP signals displayed tiny coinstantaneous variations (red arrows). Therefore, the electric outputs of the SEPS can monitor the cardiovascular status of both healthy and pathological conditions, including EP, ventricular fibrillation, and ventricular premature contractions. Such a study proved the concept and feasibility of self-sustainably powering in vivo bioelectronics by converting heart beating motions to electricity using implantable TENGs.

Subcutaneous muscle motion
Subcutaneous muscle motions from various physiological activities have also been investigated for electricity generation. In 2019, Shi et al. presented a body-integrated self-powered system (BISS) that had proven feasible for powering wearable and implantable electronics. The device was very simple, consisting of only an electrode that could be attached to the skin or implanted in the body to convert biomechanical motions to electricity. For example, when the electrode is attached to the human skin and connected to a current meter through a metal wire, electron flow can be detected, which is driven by the body electric potential (BEP). The BEP is caused by electrification of the human body during moving, such as stepping, walking, jumping, and running. The authors also demonstrated that the BISS is suitable for in vivo applications. After implanting a titanium alloy film (size of 1.5 × 2 cm²) in the back of a rabbit between the skin and muscle layer (as schematically shown in Figure 3H left), electricity was generated when the rabbit moved and drove 20 LED bulbs to flash rhythmically (Figure 3H right). The measured output performance reached $\approx 25$ V for voltage, and $\approx 80$ nA for current, as displayed in Figure 3I, which can charge a 1 µF capacitor from 0 V to 1.5 V in 100 s (Figure 3J).

Stomach peristalsis
Researchers also achieved electricity generation from movements involved in stomach peristalsis using implantable TENGs. In 2018, Yao et al. presented an implanted vagus nerve stimulation (VNS) system that was powered by a biocompatible implantable TENG (attached on the surface of the stomach), as depicted in Figure 3K.
The authors selected PTFE and Au (gold) as the triboelectric materials for the VNS device. An encapsulation layer was applied that consisted of polyimide, PDMS, and Ecoflex to ensure biocompatibility and avoid potential erosion in the physiological environment. This implantable TENG was responsive to the peristalsis of the stomach and thus generated biphasic electric pulses. After implanting the bilateral VNS (Figure 3K bottom) to the close proximity of the gastroesophageal junction, the contact/separation between the PTFE and the bottom electrode layer (BEL, namely Au), due to the stomach distending and contracting, generated electron flow between the top electrode layer electrode to the BEL via the two connections with the vagus nerve (Figure 3L). The maximum output voltage from VNS reached 0.12 V at a frequency of 2 Hz when the stomach was arbitrarily deformed. During the different implantation periods from 1 day to 12 weeks, the unchanged voltage amplitude confirmed good biocompatibility and stable performance from the VNS device (Figure 3M). Furthermore, the electricity converted by the implantable TENG can be deployed to stimulate the vagal afferent fibers to reduce food intake and achieve weight control.

**Summary of TENGs for energy**

Via the surface charging effect between thin biocompatible polymer materials, TENGs have been demonstrated to convert the biomechanical motions at various scales into electricity as a sustainable power source for on-body biomedical devices. TENGs contribute to bioengineering as a power source via two pathways. One is wearable power delivery, and some typical results from the literature are listed in Table 1. Studies on motion energy conversion, such as footfall, leg/arm motions, finger movement, and muscle stretching, were discussed. Other types of body motions that are low in intensity, like those of eye motion, were not listed here as a power source. But these generated electrical signals make more sense for sensing purposes. The other pathway of TENGs as a power source is generating electricity from the biomechanical motions of organs with implantable devices. The energy generated from these implantable TENGs is sufficient to drive a wide range of in vivo biomedical devices, as summarized in Table 2. In summary, wearable and implantable TENGs acting as power sources possess many advantages, such as versatile yet simple structures, competitive output performance, diverse material

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**Table 1. Wearable TENGs for electricity generation**

<table>
<thead>
<tr>
<th>Biomechanical motion</th>
<th>Active materials</th>
<th>Output performance</th>
<th>Power density</th>
<th>Stretchability</th>
<th>Durability</th>
<th>Washability</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>PTFE/Al</td>
<td>0.66 mA 215 V 9.8 mW/cm²</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>Bai et al. 60</td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>PTFE/Al</td>
<td>600 µA 220 V –</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>Zhu et al. 17</td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>Al foil/FEP</td>
<td>– 700 V –</td>
<td>low</td>
<td>high</td>
<td>–</td>
<td>Niu et al. 19</td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>CNT nanocomposite</td>
<td>170 nA 55 V 18.7 mW/m²</td>
<td>median</td>
<td>high</td>
<td>high</td>
<td>Fan et al. 108</td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>Rubber composite</td>
<td>– 145 V –</td>
<td>high</td>
<td>–</td>
<td>–</td>
<td>Wang et al. 20</td>
<td></td>
</tr>
<tr>
<td>Leg</td>
<td>Cu-TPE/nylon fabric</td>
<td>24 µA 480 V 750 mW/m²</td>
<td>high</td>
<td>median</td>
<td>low</td>
<td>Zhang et al. 26</td>
<td></td>
</tr>
<tr>
<td>Arm</td>
<td>LM/silicone</td>
<td>1.5 µA 64 V 8.43 mW/m²</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>Yang et al. 198</td>
<td></td>
</tr>
<tr>
<td>Arm</td>
<td>PDMS/hydrogel</td>
<td>0.36 µA 100 V 44 mW/m²</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>Liu et al. 16</td>
<td></td>
</tr>
<tr>
<td>Arm</td>
<td>PAN/PTFE</td>
<td>2.2 µA 40 V –</td>
<td>low</td>
<td>median</td>
<td>high</td>
<td>Dudem et al. 35</td>
<td></td>
</tr>
<tr>
<td>Hand</td>
<td>HBP fabric/skin</td>
<td>1.1 µA/cm² 860 V 9.46 W/m²</td>
<td>low</td>
<td>–</td>
<td>high</td>
<td>Xiong et al. 13</td>
<td></td>
</tr>
<tr>
<td>Hand</td>
<td>CF fabric/Cu</td>
<td>1.5 µA 118 V –</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>Chen et al. 109</td>
<td></td>
</tr>
<tr>
<td>Finger</td>
<td>PVA/SA</td>
<td>3.9 nA 1.47 V 3.8 mW/m²</td>
<td>median</td>
<td>–</td>
<td>low</td>
<td>Chen et al. 129</td>
<td></td>
</tr>
<tr>
<td>Finger</td>
<td>Grease elastomer</td>
<td>3 µA 115 V 383.3 mW/m²</td>
<td>high</td>
<td>median</td>
<td>low</td>
<td>Chen et al. 171</td>
<td></td>
</tr>
</tbody>
</table>

CF, carbon fiber; LM, liquid metal; SA, sodium alginate.

Values calculated based on data reported in the literature.
selections, excellent flexibility, and manufacturing scalability. These favorable characteristics are critical to make self-powered systems to meet the increasing demand for wearable and implantable electronics that require miniaturized power supply units. The direct conversion of biomechanical motions in people’s daily activities into electrical energy is a convenient, sustainable, and favored function to drive the on-body biomedical devices for personalized health care.

**BIOMEDICAL SENSING**

The electrical signals generated from TENGs in both wearable and implantable forms are generally related to the intensity, amplitude, and frequency of corresponding biomechanical motions. Thus, sensing or detecting these motions such as limb movements, pulse waves, blood flow, or the heart beat could be realized in a self-powered manner. Various wearable and implantable TENGs were developed for a wide range of biomedical sensing, including epidermal physiological signals, and in vivo organ bioactivities. In addition, electricity generation from TENGs can also act as a power source to drive other biomedical devices for health care monitoring.

**Wearable TENGs for biomedical sensing**

**Cardiovascular monitoring**

In health care, monitoring and analyzing different physiological movements, including heartbeat and pulse waves, are among the most important approaches for detecting chronic diseases such as arrhythmia, atherosclerosis, hypertension, and coronary heart disease. As discussed above, TENGs are highly responsive to body motions for electricity generation. Therefore, plentiful research has been done to develop TENGs, that act as self-powered sensors, to monitor heartbeat and pulsation using electrical signals.\(^{69-71,114,120,122}\) For instance, Bai et al.\(^ {122}\) reported a membrane-based triboelectric sensor (M-TES) that was self-powered and pressure-sensitive with high resolutions for surveillance and health monitoring. The M-TES was configured with a layered structure as schematically illustrated in Figure 4A. One of the contact triboelectric materials was a fluorinated ethylene propylene (FEP) film (thickness of 125 \(\mu m\)) that was firmly attached to the acrylic substrate, with Cu electrodes deposited on both sides. Another triboelectric material was a latex membrane (thickness of 50 \(\mu m\)). The as-fabricated M-TES device had a dimension of 3.7 \(\times\) 3.7 \(\times\) 0.2 cm\(^3\), as shown in Figure 4B. The contact (Figure 4B top) and separation (Figure 4B bottom) of the latex and FEP film, due to the

---

**Table 2. Implantable TENGs for electricity generation**

<table>
<thead>
<tr>
<th>Biomechanical motions</th>
<th>Triboelectric materials</th>
<th>Encapsulation layer</th>
<th>Mode</th>
<th>Device size</th>
<th>Electrical output</th>
<th>Degradability</th>
<th>Applications</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breathing</td>
<td>PDMS/Al foil</td>
<td>PDMS</td>
<td>CS</td>
<td>1.2 (\times) 1.2 cm(^3)</td>
<td>3.73 V, 0.14 (\mu A)</td>
<td>–</td>
<td>Powering pacemaker</td>
<td>Zheng et al.(^ {16})</td>
</tr>
<tr>
<td>Blood flow</td>
<td>nano-PTFE/Al foil</td>
<td>PDMS</td>
<td>CS</td>
<td>1 (\times) 1.5 (\times) 0.1 cm(^3)</td>
<td>(-250) mV</td>
<td>high</td>
<td>Detecting blood pressure/speed</td>
<td>Liu et al.(^ {54})</td>
</tr>
<tr>
<td>Muscle motion</td>
<td>Ti alloy film</td>
<td>–</td>
<td>SE</td>
<td>2 (\times) 1.5 cm(^2)</td>
<td>25 V, 80 nA</td>
<td>median</td>
<td>Powering pacemaker</td>
<td>Shi et al.(^ {56})</td>
</tr>
<tr>
<td>Stomach</td>
<td>PTFE/Au</td>
<td>PDMS/PI</td>
<td>CS</td>
<td>1.6 (\times) 1.2 (\times) 0.25 cm(^3)</td>
<td>0.12 V, (-40) (\mu W)</td>
<td>median</td>
<td>Adjusting food intake</td>
<td>Yao et al.(^ {74})</td>
</tr>
<tr>
<td>Pericardium</td>
<td>n-PTFE/Al</td>
<td>PTFE/PDMS</td>
<td>CS</td>
<td>3 (\times) 2 (\times) 0.1 cm(^3)</td>
<td>10 V, 4 (\mu A)</td>
<td>median</td>
<td>Monitoring cardiac activities</td>
<td>Ma et al.(^ {66})</td>
</tr>
<tr>
<td>Femur region</td>
<td>PTFE/ITO</td>
<td>PDMS</td>
<td>CS</td>
<td>2 (\times) 2 cm(^2)</td>
<td>60 mV, 1 (\mu A)</td>
<td>–</td>
<td>Promoting osteoblasts' proliferation</td>
<td>Tian et al.(^ {23})</td>
</tr>
</tbody>
</table>

Pi, Polyimide; Ti, titanium.
Figure 4. Wearable TENGs for biomedical sensing

(A–C) (A) Schematic of the membrane-based triboelectric sensor (M-TES) and (B) its photograph with the latex membrane swelling (bottom) and unswelling (top). (C) Output voltage of the M-TES as a heartbeat sensor. Inset shows the setup, including M-TES and a chest piece. Reprinted with permission from Bai et al.122 Copyright 2014, John Wiley and Sons.

(D–G) (D) Schematic of the flexible weaving constructed self-powered pressure sensor (WCSPS). (E) Photograph showing the sensor system with two pulse sensors on the human fingertip and ear for PWV and BP detection. (F) Corresponding voltage signals from the two pulse sensors. Inset shows an enlarged view of the voltage signal in one pulse cycle. (G) Systolic blood pressure (SBP) and diastolic blood pressure (DBP) measurements. Reprinted with permission from Meng et al.69 Copyright 2019, John Wiley and Sons.
pressure change inside, created the potential difference between the two Cu electrodes. Thus, electrical signals closely related to the maximum distance between the latex membrane and the FEP surface can be detected. This M-TES achieved an excellent sensitivity of $3.2 \text{ V/kPa}$ with a linearity of $R^2 = 0.98$ with pressure ranging from 3.1 kPa to 9.4 kPa. As a demonstration, the authors presented a heartbeat monitor system using M-TES. The pressure changes in the chest piece, due to the beating of the heart, are transmitted to the M-TES via air-filled hollow tubes (Figure 4C inset). The cyclic heartbeat generated a repeating change in pressure, which was converted into an electrical signal by the M-TES as displayed in Figure 4C, with an output voltage of $-0.06 \text{ V}$. The results from the tester were consistent with that of manual counting results, recording a stable heart rate of 72 beats per minute. Practicality and accuracy may pose great concern for future applications, as the TENG sensor is not directly attached to the chest for monitoring. In another study, Yang et al.71 reported a self-powered bionic membrane sensor (BMS) that is directly wearable on the neck, chest, or wrist for pulse monitoring. This BMS had a multilayered structure with a thin, oval-shaped layer of PET located at the bottom. The oval-shaped PET layer was inspired by the human tympanic membrane, enabling the BMS to monitor the external dynamic pressure with a wide range of frequencies.

In 2017, Ouyang et al.70 proposed a flexible, self-powered, ultrasensitive pulse sensor (SUPS), which outperformed the most prevalent clinical treatment, photoplethysmography (PPG) in terms of signal accuracy, reaching a high linearity of $R^2 = 0.981$. In addition, the SUPS exhibits a high peak signal-noise ratio (45 dB), as well as long-term performance ($10^7$ cycles).

Pulse wave velocity (PWV) and blood pressure (BP) can also be detected using wearable TENG sensors.69–71 Meng et al.69 developed a weaving constructed self-powered pressure sensor (WCSPS) for continuous measurement of human PWV and BP in a non-invasive manner. The WCSPS was structured with traditional woven patterns with polytetrafluoroethylene (PTFE) strips interlaced into a fabric and placed on the top of the PET substrate (Figure 4D). Vertically aligned nanowires were introduced on the PTFE surface via plasma etching to guarantee intimate contact with PET when in operation, thus improving surface triboelectrification and inducing a larger triboelectric charge density for higher electrical signal outputs. In addition, the fabricated nanowires can be easily deformed for higher measurement sensitivity to external subtle mechanical excitation. Using this WCSPS, the authors demonstrated a wearable, low power consumption sensor system for a real-time BP measurement. As shown in Figure 4E, two identical sensor systems (integrated with the WCSPS and signal management circuits) were respectively worn over the...
fingertip and the ear to detect human pulse waves. Since the time interval between the maximum value of epidermal pulse (referred to as PTT) exists in different parts (namely the finger and ear in this study) of each cardiac cycle, the BP can be calculated according to $BP = aPTT + b$ ($a$ and $b$ are undetermined coefficients). From the acquired signals of the fingertip and the ear, a $PWV = 5.96 \text{ m/s}$ was obtained with $PTT = 89 \text{ ms}$ (Figure 4F). The corresponding systolic and diastolic blood pressure (SBP and DBP) from the WCSPS system (Figure 4G) were consistent with the results from the commercial cuff-based BP measuring system (Figure 4G). This work provided a simple, cost-effective, and user-friendly approach for real-time PWV and BP measuring in humans. The WCSPS system had a sensitivity of $45.7 \text{ mV/Pa}$ with a response time of less than 5 ms, and no performance degradation was observed after 40,000 motion cycles.

**Breathing**

The tidal volume and respiratory rate of breathing patterns are important indicators of respiratory diseases. Therefore, many studies have been conducted to apply wearable TENG sensors for respiratory monitoring, both directly and indirectly.123,124 For instance, Wang et al.123 reported an air-flow-driven TENG by converting airflow from breathing into electric output signals. This TENG was responsive to the gas flow from the mouth and nose when breathing. Thus, it can be used as a self-powered real-time respiratory monitoring system. The TENG was fabricated based on a nanostructured polytetrafluoroethylene (n-PTFE) thin film. A very thin Cu film was attached to the upper surface of the n-PTFE film for charge collection with one end of the n-PTFE film fixed to the middle of an acrylic tube. When air blew into the acrylic tube, this TENG generated an average peak value of $2.4 \text{ V}$ for the output voltage and $1.7 \mu \text{A}$ for the current. The electricity generation was due to the constant contact/separation of the n-PTFE thin film with the bottom Cu electrode. The airflow rate was closely related to the electrical performance, i.e., the voltage and current, rising monotonically from $1.7 \text{ V}$ to $11.1 \text{ V}$ and $0.9 \mu \text{A}$–$10.2 \mu \text{A}$, respectively, when the airflow rate increased from $85 \text{ L/min}$ to $216 \text{ L/min}$. The authors then applied this feature to monitor human respiration patterns by embedding the TENG in a conventional facial mask (Figure 4H inset). Four different breathing patterns, including slow, rapid, shallow, and deep breathing, as shown in Figure 4H, were generated and differentiated due to their distinguished electrical signal features, including peak values and frequencies. In addition, since the accumulative charge (absolute area of the $I$–$t$ curve) and the exhalation volume are perfectly matched, this TENG sensor can also be used to quantify the volume of airflow during breathing. This parameter is another vital marker for patients with respiratory disease, such as asthma and emphysema.

For indirect breath monitoring, wearable TENG sensors can be attached to where the body motion is rhythmically related to respiration activity, such as chest and stomach fluctuation. For instance, Zhao et al.124 reported a textile triboelectric nanogenerator (t-TENG) for indirect breath monitoring by wearing it on the chest (Figure 4I). This t-TENG was woven with the 2-ply Cu-PET yarns (Cu-coated polyethylene terephthalate) as warp (vertical) and the PI-Cu-PET yarns (polyimide (PI)-coated Cu-PET) as weft (horizontal), respectively, where Cu and PI served as a triboelectric couple (Figure 4I top). Good flexibility and air permeability of the t-TENGs were achieved. The as-prepared single-layer t-TENG was stitched with a white nonelastic cotton chest strap at the two ends and situated at the upper part of the tester’s abdomen for respiratory monitoring. The authors also performed data manipulation and signal processing, which accurately derived the breathing rate based on the
time interval between two consecutive peaks (representing one complete breathing cycle from exhaling to inhaling).

Joint and muscle motions

The arms and legs are responsible for a wide range of daily life activities and are therefore abundant in biomechanical motions. For various purposes, joint motion monitoring associated with these activities is also important, especially at the advent of IoT. The finger is one of the most agile parts of the human body and can offer elaborate gestures that are successfully monitored using a self-powered wearable TENG sensor. Good wearability and sensitivity are highly preferred for these sensors as finger movements are diverse. Thin film material is a well-studied candidate for such applications. For example, Chen et al. demonstrated an ultrathin stretchable triboelectric nanogenerator (s-TENG) with a coplanar electrode for converting diverse biomechanical motions and acting as a self-powered gesture sensor. The s-TENG consists of micro-patterned PDMS and an electrospun polyurethane nanofiber film (coated with CNT and Ag nanowire) as triboelectric materials that are highly stretchable. The s-TENG was attached to the fingers’ knuckles, as shown in Figure 4J. Thus, the bending of the fingers when involved in making different gestures, for example, the signs for “love” and “victory,” caused the s-TENG to fold on specific fingers, generating corresponding electrical signals. Therefore, by analyzing each finger’s electrical signals, the gesture can be derived based on different finger bending combinations.

Similarly, arm motion and gestures can also be easily detected using stretchable TENGs. For instance, Wen et al. fabricated a transparent and stretchable wrinkled poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PEDOT:PSS) electrode-based TENG (WP-TENG). Not only did it exhibit a good energy conversion performance from hand tapping (charging a capacitor to 2 V within 3.5 min) and other human motions, but also this WP-TENG could monitor the bending angle of the elbow and inspect the motion frequency of arm movement, as illustrated in Figure 4K and L. An improved voltage was generated when the arm bending angle was raised from ~30° to 90°. Small voltage value changes were observed when the arm bending angle was fixed at ~90° while varying the frequency from 0.5 to 2.0 Hz, indicating a reliable arm position detection.

Physical exercise is a popular way of staying healthy. The correct poses or gestures while exercising is of importance to obtain optimal fitness results or to avoid any potential injuries. Given this, TENGs have been explored as a motion sensor for exercise monitoring, such as swimming and running. Zou et al. reported a bionic stretchable nanogenerator (BSNG) for underwater limb motion sensing. This BSNG was designed to mimic the structure of ion channels on the cytomembrane of the electrolyte in an electric eel, along with a mechanical control channel that was manufactured by the effect of stress-mismatch between PDMS and silicone. The unique bionic structure made the BSNG achieve a high open-circuit voltage in both dry and liquid conditions, at 170 V and 10 V, respectively. The authors also demonstrated underwater sensing applications such as human body multi-position motion monitoring during swimming. On the one hand, collecting limbs’ motion data is helpful for the users to assess whether or not the swimming progress is achieved to better deliver a personal health plan (i.e., rehabilitation training). On the other hand, these data sets are enormously useful for swimming skill analysis and strategy adjustments. The BSNG can also be deployed as an undersea rescue system. An example is swimming stroke monitoring, where the tester wears four silicone wristbands integrated with the BSNG (including a wireless data transmission system) on the elbows and
knees (Figure 4M). While swimming with different strokes, the motion signals from arms and legs can be recorded and analyzed, as plotted in Figure 4N: breast-stroke with the maximum amplitude of movement, freestyle with the highest frequency, and treading water with only leg movement. With ample information from electrical signals, including amplitude, frequency, and peak interval, this integrated BSNG system can be applied to estimate people’s physiological states underwater and coach movements and training of swimmers and deploy a rescue action in response to drowning. Furthermore, daily activity status, including slow and fast walking, standing, and running exercises, can also be monitored using TENG sensors that are capable of detecting the patterns of walking or running, such as axis acceleration and rotation. Such a capability is highly valuable especially for the elderly when fall-down happens to deliver a customized health care purpose.

The data from wearable TENG sensors can also be analyzed and employed for developing health care systems. One example is gait monitoring, which can monitor a muscle’s pressure distribution status on the bottom of someone’s feet when standing or walking. This is vital for preventing various health-related situations, especially for those with high arches. Zhu et al. designed a 3D knitted spacer fabric-based TENG by utilizing vertical contact electrification between two polymers (nylon and PTFE) with different tribo-polarities. This fabric TENG, with an effective area of only 1 cm², can reach an open-circuit voltage of more than 3 V and a short-circuit current of around 0.3 mA, indicating excellent sensing ability. The sole pressure of feet while walking is different at different positions (Figure 4O, the color changing from white to blue to green and then red corresponding to the pressure from low to high). The difference can be detected by this fabric TENG as an insole for shoes, as shown in the electrical current plotted in Figure 4P. The highest pressure occurred at the heel of the foot (position v), while almost no pressure was observed at the arch of the foot (position iv), which was consistent with predictions based on common sense. In addition, in 2019, Zhu et al. designed a self-powered textile sock utilizing a poly (3,4-ethylene dioxythiophene) poly(styrene sulfonate) (PEDOT:PSS)-coated fiber and PTFE film that was able to report the direction of movements. Four sensing gait units were sewed into the sock (TA, TB, TC, and TD) for movement monitoring, as shown in Figure 4Q. Each gait unit can be aroused depending on the walking gait. Thus, gait status and moving direction can be detected. Since socks have more application scenarios than the insole, it could expand the availability of gait monitoring data to monitor and prevent diseases, such as Parkinson’s disease for the elderly.

**Implantable TENGs for biomedical sensing**

**Cardiac biomonitoring**

In 2016, Zheng et al. demonstrated an implantable TENG for wireless and real-time cardiac monitoring, which was directly powered by harvesting the biomechanical motion of heartbeat in vivo. It had a simple multilayered structure with nanostructured polytetrafluoroethylene (n-PTFE, 50 μm thick) as one triboelectric layer (fixed on one side of the flexible Kapton film with Au layer deposited on the other side) and Al foil (100 μm thick) acting as both another triboelectric layer and the electrode. The whole device was encapsulated with PTFE and PDMS layers to enhance biocompatibility, leak-proof performance, and structural stability. To fabricate the self-powered wireless transmission system (SWTS), the implantable TENG, coupled with an implantable wireless transmitter (iWT) and a power management unit (PMU), was first implanted between the heart and pericardium as schematically illustrated in Figure 5A. The electrical signals (electricity) from the implantable TENG
were stored in a capacitor in the PMU and then transmitted to the external receiving coil through the iWT via electromagnetic waves. Subsequently, the wireless transmitted electrical data can be recorded and analyzed to extract cardiac information.

Figure 5B (top) shows the heart rate monitoring results from the SWTS and ECG at different heart rates (charging time = 10 s). (A and B) (A) Schematic of the self-powered wireless transmission system based on the implantable TENGs (iWT, implantable wireless transmitter; PMU, power management unit). (B) Top: wireless transmission signal (WTS) as received at different heart rates (charging time = 10 s). Bottom: wireless transmission signal as received at different charging times (HR = 60 beats per minute). Reprinted with permission from Zheng et al. Copyright 2016, American Chemical Society.

(C–E) (C) Comparison of heart rate data detected by ECG and the one-stop implantable triboelectric active sensor (iTENG). (D) The linear correlation between voltage outputs and SBP. Inset illustrates the mechanisms for monitoring the velocity of blood flow using iTENG. Red arrows represent the direction of blood flow. (E) The leading time and velocity of blood flow as functions of the elevation of SBP. Reprinted with permission from Ma et al. Copyright 2016, American Chemical Society.

(F and G) (F) Real-time comparison between pressure peaks derived from femoral arterial pressure, FAP (P_{FAP}) and the self-powered endocardial pressure sensor, SEPS (P_{SEPS}) based on K = 1.195 mV mm Hg^{-1}. (G) Detailed inspection of waveforms using electrocardiography (ECG), FAP, and SEPS (V_{SEPS}) outputs. Reprinted with permission from Liu et al. Copyright 2019, John Wiley and Sons.


(I and J) (I) Top: schematic view of the device with an implantable TENG for a neurogenically underactive bladder. Bottom: photograph of the device on a rubber balloon. Scale bar, 20 mm. (J) Output voltage of the implantable TENG versus the liquid volume in the balloon, V_{b}, during the filling of the balloon. Reprinted with permission from Arab Hassani et al. Copyright 2018, American Chemical Society.
different heart rates of 60, 80, and 120 beats per minute, showing an excellent linear relationship with each other ($R^2 = 0.983$). In addition, by charging for only 3 s at a heart rate of 60 beats per minute, the stored energy in the PMU was sufficient to transmit wireless data (Figure 5B bottom), showing the outstanding sensitivity and feasibility of the SWTS for real-time remote cardiac monitoring.

In the same year, Ma et al. proposed a self-powered, flexible, one-stop implantable triboelectric active sensor (iTEAS) that could provide continuous monitoring of multiple physiological signs. The iTEAS had a multilayered structure similar to other implantable TENGs, including triboelectric layers (n-PTFE and Al film), electrodes (Au and Al), spacers (titanium strip), and encapsulation layers (PTFE, PDMS, and Parylene film). To simulate the human body’s internal environment, the iTEAS (size of 3 cm × 2 cm × 0.1 cm) was implanted in a large-scale animal, the adult Yorkshire pig, and was affixed to the pericardium, with one stitch used at each corner of the device. The in vivo output performance of voltage and current reached 10 V and 4 μA, respectively. The electrical output from the iTEAS carried ample information on biomedical signals, including heart rate (HR), rhythm, and respiration rate. These electrical outputs were analyzed to quantify the aforementioned heart rhythm. For example, based on the formula of HR (beat per minute) = 60 / p-p interval (p-p interval was the time between two consecutive peaks), resting heart rate (rHR), active heart rate (aHR), and stressed heart rate (sHR) were successfully extracted from the electrical signals of iTEAS. Moreover, it was consistent with the results from commercial ECG measurements, as shown in Figure 5C, reaching a very high accuracy of ~99%. The authors also correlated the output signal of the iTEAS with another physiological signal of blood pressure by using an arterial pressure catheter (placed in the right femoral artery), as schematically shown in Figure 5D inset. The results presented a sensitivity of 17.8 mV/mmHg and linearity of $R^2 = 0.78$ between the output voltage and SBP (Figure 5D). In addition, since there was a leading time (LT) between two peaks of the voltage signal from the iTEAS and SBP signal from the femoral artery, the average velocity of blood was also derived and plotted, which is shown in Figure 5E. The relationship shows that the blood flow velocity increased, and the LT decreased when the SBP was elevated.

In 2018, Liu et al. developed a miniaturized and flexible SEPS using an implantable TENG (Figures 3E–3G). As discussed earlier, when implanting the device in the LV, the peaks from SEPS voltage showed a good match with the FAP, demonstrating excellent linearity ($R^2 = 0.974$). The systolic pressure inside the LV (PLVP) was further compared with the extracted systolic FAP, as shown in Figure 5F. A completely steady pace was nearly kept and recorded between these two signals with a sensitivity of 195 mV·mmHg$^{-1}$, demonstrating the robustness of the SEPS as an in vivo EP sensor. The authors also proved the feasibility of the SEPS for small pressure fluctuation sensing applications. By implanting the device into the left atrium (LA), a similar synchronous variation pace was found between the SEPS and FAP, as plotted in Figure 5G. In addition, the tiny notches at the top of each waveform of the SEPS (red arrow) kept pace with the small changes in the ECG waveform (P wave, purple arrow). This tiny notch was related to a slight increase in left atrial pressure when the left atrium contracted to pump residual blood in the atrium through atrioventricular valves. Moreover, this small pressure change was successfully captured by the SEPS, demonstrating its outstanding sensitivity at a pretty low level of pressure change.

Respiration rhythm
In 2014, Zheng et al. demonstrated the in vivo application of an implantable TENG to convert the thorax muscle movement during breathing into electrical signals. By
comparing the measured forced vital capacity of the rat with the output of the implantable TENG, the authors also found that both the tendency and the ratio between the inspiratory reserve volume (IRV) and expiratory reserve volume (ERV) (Figure 5H left) were nearly the same as to that between the peak values of the positive and negative current pulses (IRV/ERV = |I1|/|I2|)) (Figure 5H right). This detailed information could be useful for further respiration analysis for clinical applications.

**Bladder filling status**

In 2018, Arab Hassani et al. develop a flexible implantable TENG sensor with an actuator for underactive bladder (UAB) actuation. The implantable TENG was designed to detect the bladder’s fullness. In response, the actuation can be deployed accordingly to void the bladder for UAB patients. As depicted at the top of Figure 5I, the implantable TENG sensor was placed between the bladder and the bottom of the polyvinyl chloride (PVC) sheet. Figure 5I (bottom) displays the actual device of the implantable TENG sensor integrated with the actuator. This implantable TENG had a multilayered structure. First, a thin PET layer was placed between the PVC sheets. One Cu electrode was attached to the bottom surface of the PET layer, and another electrode at the top surface of the bottom PVC sheet. A PDMS layer and a 1 mm-thick sponge layer containing 0.2 mL DI water, acting as triboelectric materials, were sandwiched between copper electrodes. When the bladder was empty, the output voltage between the PDMS layer, water, and copper electrodes was minimal since the sponge was full of water. For the case of bladder filling, water was gradually squeezed out of the sponge. Thus, the output voltage increased, reaching the maximum value until the bladder was full (Figure 5J). Consequently, the actuator was activated and exerted a sudden force on the implantable TENG, resulting in a prompt increase in output voltage. The voiding of the bladder was to start with a concomitant output voltage reduction accordingly. Recently in the same research group, Lee et al. demonstrated mechano-neuromodulation of the autonomic pelvic nerve for bladder function in rats using a triboelectric neurostimulator integrated with a flexible neural clip interface. This technology can induce bladder contraction with micturition, showing a promising possibility of future mechano-neuromodulation.

**Summary of TENGs for biomedical sensing**

In this section, TENG-based self-powered sensors that monitor various bioactivities were comprehensively summarized. Such activities included hand gestures, gait bearing, heart beating, respiratory movement, and blood pressure. The TENGs are able to perform biomedical sensing based on their highly responsive characteristics to human body movements by generating electrical signals. The collected data from these self-powered TENG sensors can be further processed and analyzed, providing useful information on one’s health condition, stimuli perception, exercise training suggestion, etc. As a functional sensing unit in the health care system, these TENG sensors can bring rapid development to establish an autonomous BAN system with self-powered biomedical devices.

**THERAPY**

Electrical stimulation has evolved as a widespread therapeutic approach for medical treatments due to its ability to rehabilitate cells. Examples of electrical stimulation treatments include treating muscle function loss, reducing chronic pain symptoms, and relieving Parkinson’s disease by possibly activating and influencing the intracellular signaling pathways and microenvironment. Relying on a coupling of triboelectrification and electrostatic induction between soft polymer materials and biocompatible metal electrodes, triboelectric nanogenerators could efficiently
convert the biomechanical motions into characteristically high voltage and low-cur- rent electrical signals as a sustainable electrical stimulation therapeutics while avoiding collateral heat production, which is known to lead to detrimental localized side effects. To date, various treatments involved with electrical stimulation using wearable and implantable TENGs have been demonstrated both \textit{in vitro} and \textit{in vivo}, such as wound healing, laser curing, drug delivery system, hair generation, bone healing, heart disease treatments, neural stimulation, etc.

**Wearable TENGs for therapeutics**

**Cell stimulation**

The human body possesses regenerative capabilities that can be enhanced by electrical stimulation to regenerate parts of the body where cellular proliferation and differentiation are present at the cellular, tissue, or organ levels. Many treatments are often associated with cell proliferation, such as wound or bone healing, where electrical stimulation is generally applied to speed up the healing process. Accordingly, energy from wearable TENGs has been successfully demonstrated to generate electric fields that electrically stimulate cells \textit{in vitro} with decent effectiveness. In 2015, Tang et al. developed a self-powered low-level laser cure (SPLC) system, using TENG, for osteogenesis. First, the triboelectric materials of a pyramid array-patterned PDMS film and ITO were configured into a TENG. Together with an infrared laser excitation unit, the SPLC system was formed, driven by the TENG’s electricity. Using the SPLC system, the author investigated the effect of infrared irradiation on murine calvarial preosteoblasts (MC3T3-E1) for potential bone healing applications. Results from three groups, including a reference without external interferences, TENG-lasered, and battery-lasered, are compared with each other and are plotted, as shown in Figure 6A. After infrared laser curing for 2 and 3 days (each being tested separately), the cell viability of the TENG-lasered group was 15% and 10% higher than that of the reference group, respectively, indicating that the SPLC system using TENGs could be useful for promoting cell proliferation. Furthermore, the SPLC system can be directly driven by human walking when worn on the elbow (Figure 6B top). The laser was excited successfully within 60 s by typical human walking. In addition, when implanting the TENG (size of 1.5 cm $\times$ 1.0 cm) in a rat between the diaphragm and the liver, the breath of the rat was able to effectively activate the TENG with an output voltage and current of 0.2 V and 0.06 nA, respectively (Figure 6B bottom). These results show the suitability of using wearable TENGs for electrical stimulation treatment. Similarly, Tian et al., in 2019, also demonstrated the effectiveness of using TENGs on MC3T3-E1 cell stimulation \textit{in vitro}.

**Wound healing**

Wounds are inevitably present in everyone’s lives, and wound healing is of particular importance for our survival. The main goal of wound healing for a living animal is to promote rapid and effective skin wound closure. It is worth noting that antibacterial and biocompatibility qualities have to be considered when using TENGs for electrical stimulation on living animals to avoid any potential adverse effects like inflammation. In 2018, Zhang et al. reported a biocompatible triboelectric material using genetically engineering recombinant spider silk protein (RSSP). A self-powered RSSP patch was fabricated, showing outstanding antibacterial performances both \textit{in vitro} and \textit{in vivo}. The self-powered RSSP patch was built by casting the RSSP solution, which was functionalized by graphene (GR), carbon nanotubes (CNTs), and drug molecules, on a PET/ITO substrate and then assembling it with another PET/ITO substrate to form the self-powered TENG patch. Figure 6C shows the antibacterial mechanism of the RSSP patch. The post-triboelectric charged RSSP patch built a potential difference between the bacteria and positively charged surface.
Subsequently, extracellular electron transmission between the bacteria and theRSSP patch impairs the morphology of bacteria. It induces reactive oxygen species to burst the bacteria, contributing to the post-charging death of bacteria. In addition, silver (Ag) nanoparticles can be added to functionalize RSSP via bulk addition into the RSSP solution or surface modification on the RSSP patch to further improve antibacterial performance. Different doping samples show different levels of post-charging antibacterial efficiency, with the RSSP/GR/Ag patch being the most effective.
The most efficient one, killing 93% of Escherichia coli and 58% of Staphylococcus aureus. The authors also investigated the in vivo biocompatibility of the RSSP patch by placing it on a Staphylococcus aureus-infected mouse wound. After suturing and culturing for 7 days, the number of bacterial colony-forming units around the wound site were recorded and analyzed, as shown in Figure 6D. A prominent antibacterial rate of 67.4% was demonstrated, indicating the efficient antibacterial capacity of the RSSP patch.

In the wound healing process, two factors are essential: the endogenous bioelectric field and fibroblast cell proliferation, which facilitate cell migration and extracellular matrix/collagen synthesis, respectively. Both the voltage and current of TENGs, generated by harvesting biomechanical motions, can function as an endogenous bioelectric field to promote cell growth and enhance fibroblast proliferation and migration. In 2018, Long et al. reported an efficient and self-powered electrical bandage for accelerated skin wound healing that was tested in vivo on a rat using an alternating discrete electric field. The device consisted of a pair of comb-shaped dressing electrodes powered by wearable TENGs (Figure 6E top). The electrode and the TENG were configured into a bandage that can be directly worn by an animal, as schematically illustrated in Figure 6E (bottom). The TENG was working under the sliding mode by overlapping the Cu/PTFE (electronegative material) layer with another Cu (electropositive material) layer. The TENG was placed under the chest area, and the dressing electrode was facing the wounds. When the device was wrapped around the rat, the TENG converted chest movements associated with breathing to electricity, therefore introducing a discrete electric field between the dressing electrodes to assist in wound healing. For example, at a breathing rate of 30 min⁻¹, when the rat was under deep anesthesia, a peak-to-peak voltage amplitude (V_{pp}) of ∼0.2 V was recorded. When the rat’s activity was gradually increased from steady status to active status, the recorded voltage increased accordingly from ∼1.3 V (40 min⁻¹) to 2.2 V (110 min⁻¹). Figure 6F shows the results of a rat’s linear wound healing using the self-powered electrical bandage and comparing it to a control group without the device (using a dummy device). The dressing-electrode-covered region in the experimental groups showed nearly complete recovery, attributed to electric field-facilitated fibroblast migration, proliferation, and transdifferentiation. However, an unhealed wound surface was observed from all control groups, demonstrating the effectiveness of this electric bandage for skin wound healing. In addition, using this wearable TENG, the generated electric field facilitated the rapid closure of a full-thickness rectangular skin wound within 3 days compared with 12 days of usual contraction-based healing processes in rodents, enabling the possibility of fast curing. On the other hand, the alternating currents from TENGs were reported by Hu et al., in 2019, to effectively stimulate fibroblast cells (L929) for proliferation and migration. The authors found that an optimal promoting rate of proliferation was obtained when the output current was 50 μA, reaching 53.8 ± 2.66% after a two-day intermittent stimulation. Migration was found to be 67% faster (under the stimulation of 6,000 pulses per day) than that of the control group.

Hair growth
Hair loss, also known as alopecia areata, is often associated with autoimmune disorders. Currently, electrotrichogenesis by electrical stimulation is believed to facilitate hair follicle proliferation, thus inducing hair regeneration. In 2019, Yao et al. designed a wearable motion-activated electrical stimulation device (m-ESD) to promote hair regeneration via random body motions. The m-ESD is composed of two modules, as shown in Figure 6G: a TENG acting as the electric pulse generator...
and a pair of interdigitated dressing electrodes providing a spatially distributed electric field (EF). The m-ESD was wearable and could directly convert an animal’s motion energy into electricity for electrical stimulation. For hair regeneration investigation, the m-ESD was attached on the backside of the rat (Figure 6H). All the random movements of the head and neck could generate electric pulses through the TENG. When the rat was at its regular activity, its motion generated an electrical voltage, reaching a peak-to-peak value of \( \sim 320 \text{ mV} \) (Figure 6I top). This value was similar to the TENG’s output performance agitated by a computer-controlled shaker (Figure 6I bottom). By utilizing this electricity, the m-ESD can induce effective EF between the working electrodes. This EF acts on the skin and promotes the proliferation of hair follicles and hair regeneration. After 2 weeks of stimulation, the rat’s hair was relatively recovered, compared with day 0 when the hair was just shaved, as shown in Figures 6J and 6K. The authors also analyzed the hair shaft length and found that 3 V/cm EF had the most significant hair regeneration effect. This phenomenon can be due possibly to the facilitated calcium influx under this favorable EF strength (Figure 6L), which provides better stimulation to cell proliferation, hair growth factor secretion, and hair regeneration. Nevertheless, more efforts are still needed to verify the device’s effectiveness in regenerating hair from just artificial loss by shaving or natural loss due to cell senescence or cytopathy.

Drug delivery

On-demand drug delivery systems with the controlled and sustained drug release are critical for chronic and site-specific treatment. Electricity from wearable TENGs is suitable for drug delivery because not only can it provide momentum to the drug molecules, but also it promotes the permeability of the skin through the iontophoresis effect to speed up the drug molecules’ transfer rate across the dermal layers. Several studies have been reported using TENGs to power on-demand drug delivery systems sustainably.\(^{22,130}\) In 2017, Song et al.\(^ {22}\) presented the first self-powered implantable drug delivery system (iDDS) powered by the human body’s motion using TENGs (Figure 6M top). This TENG had a rotationally gating structure where two layers of metal Cu patterned with radial arrayed strips were assembled as a rotator and a stator. Between them, the triboelectric layer of PTFE was sandwiched. Output performance was controllably adjusted by increasing or decreasing the rotation speed of the rotator. With an optimization setting, an output current and voltage of 1.5 mA and 15 V, respectively, were obtained under a rotating speed of 500 rpm. For the drug delivery process, the TENG’s output was rectified and applied to Au electrodes within the drug reservoir where the water-splitting process occurred, pumping out the drug through a microtube. The authors found that higher rotating speeds generally yielded higher delivery flow rates, namely, faster water-splitting rate. When the rotating speed was 300 rpm, the TENG’s output voltage reached about 5 V, and the delivery flow rate was about 5.3 \( \mu \text{L} \cdot \text{min}^{-1} \). A higher flow rate of 40 \( \mu \text{L} \cdot \text{min}^{-1} \) was recorded at the rotating speed of 600 rpm, as plotted at the bottom of Figure 6M. The authors also carried out in vitro trans-sclera drug delivery in porcine eyes using this iDDS.

In further studies, Wu et al.\(^ {132}\) reported a wearable TENG-based on-demand transdermal drug delivery system via the iontophoresis effect that was demonstrated on a pig skin with R6G dye as a model drug. The authors found that the TENG output can efficiently accelerate the transdermal drug release rate via iontophoresis. In another study, Ouyang et al.\(^ {133}\) demonstrated a TENG-based transdermal and non-invasive delivery system to activate the iontophoresis treatment for an enhanced drug delivery efficiency. In addition, Liu et al.\(^ {134}\) reported a TENG-driven in vitro and in vivo
electroporation drug delivery system using nanoneedle-array electrodes by harvesting biomechanical energy from finger friction and hand slapping. In 2020, Liu et al. demonstrated the sustainable and controllable release of salicylic acid from a flexible drug release device for potential wound healing that is powered by arm clapping using wearable TENG. It is worth noting that both the output performance optimization of TENGs and the power-consuming control circuitry of drug delivery system with finer design are still required to obtain the exact amount of drug molecules with specified dosing rate. Although, for some cases, the wearability of TENGs involved with these drug delivery systems still needs further optimization, these reported results conceptually demonstrate the feasibility of using wearable TENGs to achieve self-powered novel therapeutic approaches in treating chronic diseases using an on-demand drug delivery system.

**Assistive physical therapy**

As auxiliary devices, TENGs have been designed to assist people with hearing disabilities. Guo et al. found that a self-powered triboelectric auditory sensor could be used as an electronic auditory system to assist and endow hearing ability by, for instance, magnifying specific frequency bands and restoring the impaired frequency region of deaf voice to nearly normal voice. In 2020, Zhou et al. reported a TENG-based sign-to-speech language translation glove using a yarn-based stretchable sensor array (YSSA) that could facilitate communication between signers and non-signers. The sensing unit’s core consists of a conductive yarn coiled around a rubber microfiber with the entire body sheathed by a PDMS sleeve. This yarn-based stretchable sensor was intrinsically stretchable due to its unique coiled structure and sensitivity for energy conversion and motion detection. To enable the real applicability and robustness of this glove for its sign-to-speech translation, authors collected and analyzed a total of 660 sign language hand gestures based on American Sign Language by taking advantage of machine-learning algorithms. The YSSA system has a high recognition rate of 98.63% and a short recognition time of less than 1 s. With external devices such as cellphones, the hand gestures from this intelligent YSSA glove can be displayed on a screen in real-time with corresponding text and voice being displayed and played from the speaker or cellphone with built-in capability to convert text into speech.

**Air cleaning**

Under the globally intensive industrial activities, human health is significantly threatened by serious environmental problems including particulate matter (PM) and gaseous pollutants, such as volatile organic compounds, SO₂, and NOₓ, that may result in asthma, chronic bronchitis, and even getting poisoned. TENGs, as a high voltage source, are demonstrated to purify the atmospheric and indoor air via the electrostatic adsorption effect and generate negative air ions (NAIs) from carbon fiber electrodes. The air cleaning capability of TENGs plays a significant role in sustainably improving the quality of living environment, and eventually achieving health care for all human beings. For instance, to purify polluted air, Chen et al. reported a rotating triboelectric nanogenerator (R-TENG) that was capable of generating a high voltage around 300 V and current 3.4 mA, achieving both efficient electrostatic precipitation of dust and SO₂ oxidization without producing byproducts. Furthermore, an SE triboelectric nanogenerator in a fabric form was developed using the photocatalyst-embedded and polymer-coated stainless steel wires as the output terminal. The authors reported that the formaldehyde degradation rate was achieved at twice the rate compared with the control experiment because of the strong adsorption of molecules from the TENG-induced high electrostatic field. These examples, as indirect ways of biomedical treatments, to potentially
reduce the possibility of contracting a disease, is promising for continuous PM and gaseous pollutants removal from both the outdoor and indoor air that has exerted a huge impact on human health. Very recently, with a rationally structure design of TENGs, Guo et al. obtained a voltage production of more than 2000 V to produce $2 \times 10^{13}$ NAIs. They also prototyped a PM 2.5 removal from 999 to 0 $\mu$g m$^{-3}$ within 80 s, which was expected to potentially contribute to the artificial NAI generation and thus improving our living quality, such as relieving symptoms of allergies to dust and mold spores as an alternative biomedical treatment. Although the output from TENG is useful for air purification, currently, the mechanical motions to drive TENGs was rarely from the direct human body movements. The adjustment of air cleaning devices using body motion-generated electricity is very promising for breath disease therapeutics. Nevertheless, applying the high-voltage output from TENGs to the ambient air and therefore improving the air quality for pollution control or individual health needs will be a research hotspot.

**Implantable TENGs for therapeutics**

**Tissue regeneration**

Bone healing is usually associated with long-term treatments that span from days to months. In light of this, in vivo electrical stimulation was reported to accelerate tissue regeneration, such as osteoblast proliferation, using implantable TENGs for potential bone healing. In 2019, Tian et al. proposed a self-powered flexible and implantable electrical stimulator to promote osteoblast differentiation and bone remodeling for potentially alleviating osteoporosis and osteoporosis-related fractures. This electrical stimulator consists of an implantable TENG that is combined with a flexible interdigitated electrode (to generate an EF for cell stimulation). For the in vivo study, the size of the electrical stimulator is controlled at $2 \times 2$ cm$^2$ as shown in Figure 7A. After implanting the electrical stimulator in the surface of the femur region of a rat, the rat’s daily activity agitated the TENG for electricity generation, reaching a voltage, current, and transferred charge of around 60 mV, 1 nA, and 0.04 nC, respectively. The murine calvarial preosteoblasts (MC3T3-E1) cell stimulation results using this electrical stimulator were analyzed, including cell attachment, spreading area, alignment, differentiation, and the level of intracellular Ca$^{2+}$ by the analysis of extracellular alkaline phosphatase (ALP) levels. As shown in Figure 7B, after 18 days of culture, the cells with electrical stimulation treatment (EF group) were spreading fully, and the spreading areas were much greater than the control group, with good cell arrangement and orientation nearly parallel to the EF orientation. After electrical stimulation for 12 and 18 days, the extracellular ALP levels were 28.2% and 10.2% higher than the control group, respectively, indicating that bone matrix synthesis was effectively activated using this electrical stimulator (Figure 7C). The authors also found that the high Ca$^{2+}$ levels in the EF group (activating the Ca$^{2+}$ signal transduction pathway, thus increasing the Ca$^{2+}$ influx) were responsible for improved cell adhesion and proliferation.

**Cardiac rehabilitation**

The heart is the central organ involved in blood circulation to the rest of our body. Therefore, our overall health is highly dependent on the health of our hearts. For this reason, safe and effective in vivo treatments of heart-related diseases becomes increasingly important. In 2014, Zheng et al. demonstrated an in vivo TENG-powered pacemaker that harvested the biomechanical motion of a rat’s periodic breathing. As discussed earlier in Figures 3A–3D, the authors demonstrated that a capacitor could be charged from 2 to 3 V within 275 min (for a total of 13,750 breathing cycles) by the implantable TENG to power the pacemaker prototype. The output current of a single stimulation pulse of the pacemaker prototype reached about...
25 μA, comparable with commercial pacemakers. Furthermore, this implantable TENG-powered pacemaker can also be used to regulate the rat’s HR. In 2018, Jiang et al. developed a bioabsorbable natural-materials-based TENG (BN-TENG) that was successfully used as a voltage source to accelerate the beating rate of dysfunctional cardiomyocyte clusters in vitro. The authors investigated several natural materials for BN-TENG fabrication, including cellulose, chitin, silk fibroin (SF), rice paper (RP), and egg white (EW). For example, a BN-TENG, composed of SF and RP as triboelectric layers, showed a maximum output voltage and current of 34 V and 0.32 μA, respectively. Using the electricity from the BN-TENG for cell stimulation in vitro, the authors found that the four cardiomyocyte clusters’ beating rates accelerated.
significantly. The average pause time between the cardiomyocyte cluster’s two beating cycles was greatly reduced from 1.382 s to 0.606 s after stimulation. In addition, the variation of beating rates after stimulation also decreased significantly, demonstrating the improved consistency of cell contraction and the potential for repairing the abnormal cardiomyocytes.

Very recently, in 2019, Ouyang et al.\textsuperscript{55} demonstrated a fully implanted symbiotic pacemaker (SPM) based on an implantable TENG, which achieved energy conversion and storage as well as cardiac pacing on a large-scale animal. As illustrated in Figure 7D, the SPM consists of three parts: the energy conversion unit (namely the implantable TENG), the PMU, and the pacemaker unit. The implantable TENG, with triboelectric materials of n-PTFE and Al foil, harvested the periodic motions of the heartbeat directly and charged a capacitor within the PMU from 0 to 3.55 V within 190 min under an HR of \( \frac{24}{77} \) beats per minute. The energy converted from each cardiac motion cycle was 0.495 \( \mu \)J, which is higher than the required endocardial pacing threshold energy (0.377 \( \mu \)J). Using this self-powered SPM, the pacing of a pig’s HR was demonstrated by implanting the device into the chest. After continuously generating electricity from cardiac motions, in \( \sim 200 \) min, the SPM was switched on to release the pacing stimuli based on ECG measurements shown in Figures 7E and 7F. The typical P wave, QRS complex, and T wave could be identified in the ECG of intrinsic rhythm (Figure 7E). After releasing the pacing stimuli, a heart contraction and a stimulated QRS complex were observed in the ECG. Here, the stimulated QRS complex appeared immediately following the pacing stimulus, indicating the heart was successfully paced by SPM (Figure 7F). This symbiotic system got energy from the heart’s beating using an implantable TENG and then achieved cardiac pacing via a pacemaker to reactivate the heart, demonstrating a unique self-powered approach for other symbiotic bioelectronics.

**Muscle rehabilitation**

Muscle function loss, which can lead to the loss of control of regions of the body, is a consequence associated with many diseases, including stroke, spinal cord injury, and multiple sclerosis.\textsuperscript{139} Electrical stimulation is a rehabilitative and therapeutic strategy that could help and even recover patients’ abilities to move. Accordingly, TENGs have been demonstrated to be an effective power source for muscle stimulation.\textsuperscript{25,140,141} In 2017, Lee et al.\textsuperscript{140} reported a stacked TENG with a peak-to-peak voltage of 160 V and a current of 6.7 \( \mu \)A to power neural interface electrodes for neural stimulation. The authors placed the electrode around the sciatic nerve and recorded compound muscle action potentials from the gastrocnemius medialis and tibialis anterior (TA) muscles. They found that a current of 2.4 mA can activate muscles. Muscle twitch and contraction were observed, and they became stronger when the TENG was agitated by hand tapping at higher frequencies. Wang et al.,\textsuperscript{141} from the same research group, later developed a multiple channel intramuscular electrode that was capable of mapping motoneurons in the muscle tissue, therefore enabling high efficiency of muscle stimulation using a TENG at a short-circuit current of 35 \( \mu \)A. The high threshold current required for direct muscle stimulation makes the superior efficiency of TENGs stimulators incomparable. In 2019, Wang et al.\textsuperscript{25} reported a new configuration of diode-amplified TENGs (D-TENGs) to improve direct muscle stimulation effectiveness significantly, as schematically illustrated in Figure 7G. The D-TENG (size of 8 \( \times \) 8 cm\(^2\)) contains Al-PTFE as triboelectric surface pairs with a multilayered structure (Figure 7G top). The diode is connected in parallel with the D-TENG with an additional mechanical switch (Figure 7G bottom left). The charge generated by all layers of D-TENGs can be accumulated in front of the diode and transferred together within a shorter duration to achieve a short and
high current pulse (Figure 7G bottom middle). This amplified current pulse is sufficient and effective for direct muscle stimulation through a neural interface implanted in the muscle (Figure 7G bottom right). The D-TENGs can boost the current pulse frequency up to 500 Hz to match the resonance frequency of motoneurons in muscles.

**Neural stimulation**

Many bodily actions are dictated by signals from the peripheral and central nervous system (PNS and CNS). Thus, functional loss from many nerve injuries is due to the signal transmission loss from nerves to muscles. Given this, electrical stimulation helps patients with nerve injuries by restoring the bioactivity of specific muscles. In 2016, Zheng et al.\(^5\) observed the orientation of nerve cell growth under the stimulation of two complementary micrograting electrodes powered by an implantable TENG, demonstrating the feasibility of using implantable TENGs for the neuron repairing process. Successfully modulating different leg muscles to twitch and contract, Lee et al.\(^142\) took a step forward in the selective stimulation of a sciatic nerve in a rat using a water/air-hybrid TENG. Later on, nerve stimulation using implantable TENGs has been confirmed to regulate food intake to achieve weight loss by stimulating the vagus nerve.\(^176\) In 2018, Yao et al.\(^76\) reported an implanted VNS unit that was driven by a biocompatible TENG in vivo. This TENG, attached to the stomach’s surface, was responsive to peristalsis, generating biphasic electric pulses that could stimulate vagal afferent fibers to reduce food intake and achieve weight control. The authors investigated the effectiveness of VNS compared with several control groups, as the results show in Figure 7H. Sham (rats with VNS but without Au leads connecting the Cu wire electrodes to the vagus nerve, see Figures 3K and 3L), Lap (rats with surgery but without the VNS device implantation), and Intact (rats without any operation) groups are defined as the control groups. After implantation surgery on the adult rats (500g), the Lap group exhibited no difference compared with the intact group. The Sham group quickly recovered to the same levels after the initial drop in body weight. The average bodyweight of the VNS group exhibited a steep drop over the first 25 days after implantation, followed by a small recovery and stabilization at ~400 g (~28% reduction compared the control groups). Figure 7I shows the obvious body size reduction by implanting the VNS device for weight control. This work confirms the effectiveness of using implantable TENGs as an energy source for electrical stimulation for weight control.

**Cancer therapy**

Implantable TENGs have been reported as power sources to drive drug delivery systems in vivo via electrical stimulation, achieving a controllable drug release approach. One example is presented by Zhao et al.,\(^143\) in which they use Doxorubicin (DOX)-loaded red blood cells for anti-tumor treatment where the drug release rate is upregulated using an implantable magnet triboelectric nanogenerator (M-TENG). The authors applied two magnets with a diameter of 8 mm fixed on the back of the two friction layers to separate them via magnetic repulsion during CS cycles. This structure design guaranteed the detachment of the two friction layers for each cycle even after long-term cyclic tests with an open-circuit voltage and short-circuit current of 70 V and 0.55 \(\mu\)A, respectively. As a comparison, the self-release of DOX from red blood cells was in the low range. However, a much quicker release of DOX was observed after electrical stimulation using electricity from the M-TENG. The fast release rate was immediately stopped after the withdrawal of electrical stimulation. Consequently, the controllable release of DOX at a low drug dosage resulted in an improved killing efficiency of cancer cells.
As demonstrated in various in vivo therapeutic applications using implantable TENGs, the self-sustainable feature positions implantable TENGs as a favorable candidate compared with conventional battery-based therapeutic devices. Notably, the biodegradability of implantable TENGs minimizes the possibility of secondary surgeries once their function cycles have been completed. Depending on the application, whether it is of short-term or long-term implantations, the biodegradability of implantable TENGs needs to be considered to avoid secondary surgeries.\(^5,21,39\) In 2016, Zheng et al.\(^5\) reported a biodegradable triboelectric nanogenerator (BD-TENG) for in vivo biomechanical energy conversion, which could be degraded and resorbed in an animal body after completing its work cycle without any adverse long-term effects. The BD-TENG was fabricated with biodegradable polymers (BDPs) and resorbable metals. The performance of the BD-TENG can be tuned according to its required degradation features and performance parameters, using different materials, including poly(l-lactide-co-glycolide) (PLGA), poly(3-hydroxybutyric acid-co-3-hydroxyvaleric acid) (PHB/V), poly(vinyl alcohol) (PVA) and poly(caprolactone) (PCL) (from positive to negative in terms of “triboelectric series”). In application, the open-circuit voltage of the BD-TENG can be tuned from \(\sim10\) V up to \(\sim40\) V. A current of 1 \(\mu\)A and power density of 32.6 mW m\(^{-2}\) for the BD-TENG was achieved when PLGA/PCL were selected as triboelectric layers. Figure 7J shows the in vitro degradation images of the BD-TENG encapsulated with the PLGA layer after NaOH incubation for different times. After 40 days, significant mass loss and structure disintegration were observed. For the in vivo degradation test, the output voltage of PLGA-coated BD-TENGs was markedly decreased from 4 to 1 V for the first two weeks of implantation (Figure 7K). When PVA was the encapsulation layer, the BD-TENG could work for over 24 hr in vivo (output, \(\sim3\) V), and it almost entirely dissolved within 72 hr. The authors also applied the BD-TENG to power two complementary microelectrodes (generating a DC-pulsed EF) to stimulate nerve cell growth with significant cell orientations observed. Given its remarkable biocompatibility and tunable degradation property, this BD-TENG possesses great potential for transient medical devices. In 2018, Jiang et al.\(^{21}\) selected several natural materials, including cellulose, chitin, SF, RP, and EW, to design various fully bioresorbable natural materials based TENGs (BN-TENGs). Since these natural materials possess different electron affinities, the electrical output of the BN-TENG varies, from 8 to 55 V in terms of voltage and from 0.08 to 0.6 \(\mu\)A in terms of current, by pairing different materials. The in vivo and in vitro operation time of BN-TENG was modulated from days to weeks by modifying the SF encapsulation film.

**Summary of TENGs for therapeutics**

In this section, the wearable and implantable TENGs used as therapeutic devices for biomedical applications of potential human health care were extensively reviewed. Successful demonstrations were conducted in animal models to achieve various functionalities, such as wound healing, a pacemaker for heartbeat regulation, bone healing, hair generation, and weight control, among others. These advancements lay great foundations for developing the integrated autonomous BAN system with the capability of on-demand treatments that could potentially be guided and driven by TENG-based sensors and power sources, respectively.

**AUTONOMOUS BAN**

Advancements in integrated circuits, soft conductors, and wireless communication technologies have enabled the realization of a wireless body area sensor network that allows unobtrusive, continuous, and long-term health monitoring. Furthermore, these advances have provided real-time updates on a patient’s status to the
physician, thus assisting therapeutic schedule optimization. But patients, who use wearable or implantable therapeutic devices, would still need to go to clinics, as the technology to guide the therapeutic devices’ function execution based on the health status monitoring data is still limited. In addition, the power supply for current therapeutic devices is mainly dependent on batteries, which possess distinct disadvantages such as limited lifetime, periodic replacement, and toxic potential. Therefore, establishing an autonomous BAN that combines energy, sensing, and therapeutic devices in an integrated system with efficient information communication and exchange is highly desired.

System integration

As power sources, TENGs have been widely investigated to successfully drive bioelectronics such as pacemakers, blood pressure/speed sensors, and drug delivery systems, or charging other energy storage devices, such as supercapacitors and lithium batteries. They also display comparable sensing performances for monitoring various human body motions and physiological activities. In addition, therapeutic devices successfully realize their functions by using the power from wearable or implantable TENGs or these TENG devices themselves can exert therapeutic effects. As depicted in Figure 8 (left), through harvesting biomechanical energy around the human body via wearable and implantable TENGs, the generated electricity can either be stored in a battery to drive therapeutic devices or directly used as signals for self-powered sensing for body status monitoring. Simultaneously, the ample information from TENG sensors could be on-site processed and serve as personal health profiles to guide tailored treatments and track the treatment progress. Such a closed-loop BAN system via wearable and implantable TENGs is tremendously promising for personalized health care: (1) the cooperation between sensing and therapeutic nodes can deliver the closed-loop medical care in a self-adaptive and self-administered manner; (2) TENG-based energy nodes in the BAN allow these systems working independently without reliance on external power sources. However, the seamless hybridization of energy, sensing, and therapeutic components in a BAN system is challenging when simultaneously considering functionalities such as power storage and management, signal readout, conditioning and wireless transmission, and optimized therapeutic treatments.

Figure 8. Autonomous body area network for personalized health care
Left: a BAN system built on wearable and implantable TENGs by converting various biomechanical motions around humans to electricity to establish the closed-loop system of energy, sensing, and therapy for personalized health care.
Right: the challenges and promising solutions for the BAN system.
In 2016, Zheng et al.\textsuperscript{16} reported an \textit{in vivo} TENG-based self-powered wireless cardiac monitoring system via electromagnetic waves that consisted of an implantable wireless transmitter (powered by the implantable TENG from harvesting the heartbeat motion of an adult swine) and an external receiving coil. Although they achieved a comparable sensing performance compared with commercial ECG, further advancements are highly desired in order to use the collected heartbeat signal as information to guide implantable therapeutic devices, such as the self-powered pacemaker, to treat heart-disease-related symptoms.\textsuperscript{16,55} Similar implications can be made for many other health care problems such as weight control,\textsuperscript{76} underactive bladder actuation,\textsuperscript{93} and hair regeneration,\textsuperscript{26} where sensing, therapy, and energy can be simultaneously realized via a “one-stop” TENG-based autonomous BAN system. With advances in artificial intelligence for signal processing, the closed-loop TENG-based integrated systems for personalized health care can be used anywhere and at any time, with a reduction in unnecessary visits to the clinic. Nevertheless, as summarized in Figure 8, several challenges still need to be surmounted to achieve a fully autonomous BAN system using wearable and implantable TENGs.

\textbf{Data and power in BAN}

In addition to materials innovations for both wearable and implantable TENGs, efficient data and power transmission among different TENG-based nodes (i.e., the power source, sensing and therapeutic devices) within the BAN system is critical and quite challenging. Given this, specially designed and tailored circuit operating system for TENGs is one of the crucial strategies to pursue advanced performance of the BAN system for bioengineering applications. Such operating system offers various functionality that addresses a range of technical design problems, including sensors, signal processing and (wireless) communication, power source management and transmission, and networking. Sensors can be derived from applied physics or from analytical chemistry, which convert physiological signals into electrical signals. In addition, the data processing unit capable of converting the generated analog signals into digital signals needs to be designed according to the sensor type. For instance, the on-site sensing data processing, especially for implantable applications, is crucial to the timely function execution of therapeutic devices. But how to guarantee the stable information flow from sensing devices to therapeutic devices via wire or wireless approach is still under investigations. Conductive wires may bring up more device design requirements while wireless technology may have power consumption issues. Nevertheless, low power consumption technology such as near-field communication, as promising wireless approach, is under study. Furthermore, power units can employ energy harvesting, energy transfer, and power management technologies. And power supplying systems, including flexible batteries, flexible supercapacitors, and (wireless) charging technologies, are also encouraged. Currently, although the peak output voltage of wearable TENGs could reach hundreds of volts, it is still not as sufficient as current LIB batteries that deliver stable, sustainable, and real-time energy for consumable devices. Thus, more efforts need to be devoted for optimizing the output performance and building efficient power management system. Xi et al.\textsuperscript{144} proposed a novel yet universal power management strategy to autonomously release about 85% of energy from the TENG as a steady and continuous DC voltage on the load resistance. This may provide a rational design that could help with the power management system development and attract further future research on this topic.\textsuperscript{50,145} Lastly, in the BAN system, the wire/wireless unit would deliver the aggregated data from processing units to the nearest gateway node or to remote servers responsible for data analysis, device-to-device (D2D) communication, and Internet reaction. Several hardware solutions and protocols...
have been developed to address the needs of various sensor networks. This is one of the critical components of wearable bioelectronics as it regulates the modalities of network communications, and it usually has the most significant impact on the power consumption of the device. Hence various criteria should be taken into accounts, such as transmission range, data rate, power consumption, and bandwidth.

SUMMARY AND PROSPECTS

With the rapid advancement of IoT and 5G wireless networks, on-body biomedical devices enable the change of current reactive and disease-centric health care system to a personalized model with a focus on disease prevention and health promotion. Resulting from unique working principle, triboelectric nanogenerators that could convert the biomechanical motions into sustainable electricity by using the surface charging effect between thin polymer membranes, are becoming an emerging and compelling biotechnology to promote the health care transformation. The electricity generated from biomechanical motions via TENGs could be utilized for self-powered biomedical sensing, therapeutic stimulation, and sustainably powering biomedical devices (Figure 9). In this section, both major achievements and challenges in the field of TENGs for bioengineering are discussed. Perspectives on potentially overcoming these challenges are also proposed.

Wearable TENGs

For wearable TENGs, the high-voltage output can be readily obtained by scavenging limb motions such as hand tapping, arm/leg shaking, and footfall that can directly light up several dozen LEDs to light up and run small electronic devices like watches and calculators. Electricity from small motions, including finger bending, eye blinking, muscle stretching, etc., cannot be directly utilized for a sustainable power source owing to the limited output performance. However, the output signals themselves are excellent indicators for daily activities monitoring. Much work has been done on the optimization of both output performances and sensing properties of wearable TENGs via introducing physical (i.e., surface...
micro/nano-structures) or chemical (heterogeneous element doping) modifications onto triboelectric materials. In addition, wearability is critical for practical applications. Thus, flexible, stretchable, fabric-based, and on-skin TENGs are reported. Demonstrations on health care are also reported for wearable TENGs that extend their application to on-body electrical stimulation (Figure 9A). Nevertheless, several problems need to be addressed for the promotion of extensive applications and additional improvements to wearable TENGs (Figure 9B).

**Wearing comfort**

There are several reasons why people may not enjoy using wearable devices. The most discussed is wearing comfort. In this respect, new approaches and materials must be explored to break through conventional methodologies’ limits. Thus, the design of wearable TENG devices should comprehensively integrate with clinical experiment; show humanistic care to the marginal and disadvantaged people. At the same time, prosperous functions, industrialized design, science fiction appearance, and a friendly machine interface need be continuously pursued, starting from the overall design and the background of materials science, aesthetics, as well as rehabilitation science. For instance, fabric-based TENGs are attractive for developing a wearable energy conversion system as fabrics and textiles are the basic building blocks of clothing. Embroidery is even integrated with a TENG system for daily motion energy conversion. The electricity generation function of fabric TENGs is well rationalized; however, several wearability factors are less investigated, including permeability, drapability, fabric handle, etc. Wearable TENGs only used as a jacket or coat may care less about these factors since they do not directly contact skin. However, directly putting TENGs on the skin requires even more studies. These on-skin TENGs need to be compatible with the skin, flexible, stretchable, etc. Conforming to contours of various regions of the body requires rational materials selection and fabrication processes. The less addressed adhesion strength issue between on-skin TENGs and skin also poses a great challenge for real applications. Furthermore, air permeability is a key parameter for the skin-mounted device. Instead of using continuous film as the substrate for TENG fabrications, non-woven fabric with nano-to microscale fibers could be a great candidate that provides relatively high air permeability, making the device breathable.

**Durability and stability**

Since mechanical friction, bending, and extension are universally present with all wearable devices, material wear cannot be avoided, which may be detrimental to device performance. Thus, a self-healing capability is an attractive functionality for wearable TENGs, especially for on-skin devices. For instance, the incorporation of photothermally active polydopamine particles and multiwalled carbon nanotubes (MWCNTs) allows poly(vinyl alcohol)/agarose hydrogel-based TENGs to be physically self-healed in ~1 min upon exposure to near-infrared (NIR) light. However, the output performance after healing and the physiological response from the human body require further studies. In addition, washability for fabric TENGs is important for daily wearing, which may be resolved by selecting hydrophobic triboelectric materials or encapsulating them with waterproof wrappers. Nevertheless, the mechanical durability of applied materials needs further and careful studies, as washing conditions, are particularly complicated and challenged.

Generally, the conversion from body motions to electricity using wearable TENGs is associated with relative movements of triboelectric materials within the device through the four working modes. The operation stability of wearable TENGs for bioengineering could be primarily determined from two aspects. One is the material
wearing. Abrasion may occur that could gradually deteriorate the performance, affecting stability for long-term applications. Furthermore, the performances of TENGs also highly rely on the quality of surface nanopatterned treatment that could improve the output performance. The failure of low mechanical resilience of these nanopatterns is detrimental to the stability of electrical output. Thus, more studies on material performance optimization and reliable functionalization strategy are required. Other situations, like operations in harsh conditions of high temperature and humidity, also bring concerns for the operation stability. In addition, developing anti-noising capability is significant for wearable TENGs to cope with the dynamic environments. When wearable TENGs are directly or indirectly attached to the body as a self-powered sensor for motion monitoring, they are subject to abundant interferential body movements, which may arouse unexpected disturbing signals that deteriorate sensing performance. Improvements in the anti-noising capabilities of TENGs are challenging and are still being explored.

Implantable TENGs
Implantable TENGs have been rapidly developed thanks to TENG’s capability to convert motions with low intensity and small amplitude to electricity such as heart beating, breathing, muscle motion, etc. Various demonstrations on scavenging organ motions to power in vivo biomedical devices are reported, including the pacemaker, muscle stimulation, actuation, etc. Encapsulation materials of implantable TENGs are also assessed to ensure biosafety, including PDMS, PLGA, and other biocompatible natural materials that protect implantable TENGs from any leakage of biofluid for in vivo application. Physiological activity sensing is realized using a self-powered TENG sensor by harvesting in vivo ambient biomechanical energy. An in vivo stimulator system is also prototyped to accelerate cell proliferation and control cell activity such as bone healing, regulating heart rhythm, weight control, etc (Figure 9C). Since implantable TENGs are a new yet rapidly developing technology for in vivo applications, extensive and in-depth research is crucial to fully understand their performance and mechanism requirements for various applications in the near future (Figure 9D).

Biosafety
Output performance is not the only metric that is essential for in vivo biomedical treatment. Biosafety is very important for eliminating possible side effects or other sufferings for patients as well. The biocompatible encapsulation material is a popular option that avoids direct contact between the tissue and implantable TENG device. However, leakage occasionally happens, especially for long-term applications where biofluid may flow into the implantable TENG devices, interrupting their functions. Even worse, the device’s materials may go into the in vivo environment, which is detrimental. Currently, most results are from studies that are conducted in vivo for only a few weeks. Therefore, biosafety is a priority, not just as an encapsulation layer but also for material selections for the implantable TENGs devices’ components. More work on biosafety assessments of materials and fabrication approaches for both short-term and long-term applications is required.

Multifunctionalities
Multifunctionalities are usually required for implantable devices, including at least powering, sensing, and curing. How to implement these functions using implantable TENGs for bioengineering with a seamless integration is challenging. Most current studies are associated with small animals whose organs are even smaller. Implantable TENGs with the CS mode are only allowed to operate in a narrow space, making the device’s functionality limited. Thus, the trade-off between the small device for
better implantation and the large device for higher output performance and multifunctionalities has to be deliberately optimized. For instance, powering therapeutic devices for both monitoring, diagnosis, and curing may require higher energy output performance of the TENGs. However, such an integrated system needs to be compatible with the implanting regions of organs in terms of dimensions and functions. In addition, large-scale in vivo animal studies need to be addressed in the future. With the miniaturization of devices as the first step, an integrated system with multifunctionalities is of great significance to achieve minimally invasive surgeries of implantable TENGs for clinical treatment to reduce the risk of infections, injury, or other sufferings.

**Efficient device fixation**
How to anchor the implanted TENG devices onto the body tissue is underexplored and needs extensive investigation for stable and long-term device operation. One direction is the mechanical anchoring that minimizes the potential injury. Non-destructive approaches such as adhesives are preferred to attach implantable TENGs to the target organ in vivo. The adhesive layer needs to maintain long-term adhesion, which should last until the end of the implantable TENG devices’ functional cycle. Aqueous conditions in the body due to biofluid make the adhesive aspect of implantation challenging. Therefore, this problem presses for a solution and needs future in-depth studies.\(^{148,149}\)

**Wireless data transmission**
Implementing implantable TENGs as in vivo sensors or therapeutic stimulators for clinical treatment needs to be monitored in real-time as feedback for further therapeutic adjustment. Wireless data transmission from implantable TENGs to a control panel is preferred since wirelines make the device cumbersome and unfriendly to patients.\(^{67,68}\) However, widely-adopted wireless communication technologies, such as Bluetooth (BLE) and Zigbee, highly rely on rigid chips, and their energy consumption is relatively high. To make a battery-free and small size implanted wireless device, one of the most promising approaches is to let TENG drive the near-field communication coil for energy/signal transmission. However, due to TENG’s excessive internal resistance, the generated voltage is difficult to be transferred to the coil, resulting in a low energy/signal transmission efficiency.\(^{150}\) Recently, ultrasound was reported as a mechanical energy source for both electricity generation and signal communication using TENGs via a wireless manner.\(^{151}\) Nevertheless, the output (in the range of several volts or less) needs further optimization for obtaining an improved signal-to-noise ratio of wireless data transmission. Thus, using TENGs to drive coils to efficiently transmit energy and information needs more research input.

**Degradability for customizable treatment**
One compelling feature for degradable bioelectronics is the elimination of potential secondary surgery that may cause infection or tissue lesion. Although degradability is preferred, especially for short-term applications, the trade-off between output performance and the degradability of the implantable TENG devices must be thoroughly considered due to the complexity of the in vivo physiological environment. The stability of electrical signals and in vivo performance of these devices are crucial to retrieve clinical parameters and provide therapeutics that are tailored to the disease of individual patients. Natural materials are good options, including cellulose, chitin, SF, EW, and so on, which are even bioresorbable to avoid any side effects. However, the physical and chemical properties of either natural materials or other BDPs need to be systematically studied and engineered (i.e., the relationship between degradation period and output performance) for optimized therapeutic functions and individualized treatment requirements.
FINAL REMARKS
In conclusion, recent advancements of wearable and implantable TENGs that could efficiently convert the biomechanical motions into electrical signals for energy, sensing, and therapy have been comprehensively reviewed. Their applications for clinical treatments integrated with various biomedical devices are rapidly expanding. Leveraging TENGs with various functionalities has the potential to build up an autonomous BAN capable of providing personalized health care without relying on external power sources. Benefiting from the unique working principle, TENGs hold a collection of compelling features, including light weight, structural simplicity, softness, flexibility, biocompatibility, and extremely high voltage output, rendering them very competitive in the bioengineering field. The TENGs-enabled BAN could be able to seamlessly integrate both wearable and implantable power sources, biomedical sensors, therapeutic devices, low power consumption microcontrollers, and internet connection to form an autonomous, intelligent, closed-loop sensing and therapeutic system, which would propel the medical fields in the era of IoT.

RESOURCE AVAILABILITY
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Data and code availability
Data available on request from the authors.

Materials Availability
All materials available on request from the authors.

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AUTHOR CONTRIBUTIONS
J.C. launched and supervised the project. S.Z. and J.C. built the framework and organized the figures. S.Z. wrote the initial manuscript under the guidance of J.C. All authors have provided feedback and contributed to the manuscript writing.

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