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FEATURE ARTICLE

Advancements in flexible biomechanical energy harvesting for smart health applications

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Advancing flexible electronics enables timely, smart health management and diagnostic interventions. However, current health electronics typically rely on replaceable batteries or external power sources, requiring direct contact with the human skin or organs. This setup often results in rigid and bulky devices, reducing user comfort during long-term use. Flexible biomechanical energy harvesting technology, based on triboelectric or piezoelectric strategies, offers a promising approach for continuous and comfortable smart health applications, providing a sustainable power supply and self-powered sensing. This review systematically examines biomechanical energy sources around the human body, explores various energy harvesting mechanisms and their applications in smart health, and concludes with insights and future perspectives in this field.

1. Introduction

Over the past few decades, smart health has emerged as a highly promising field in patient care as a way to leverage electronic devices to capture real-time health data. It encompasses a range of technologies designed to monitor, analyze, and enhance physical well-being by providing continuous, data-driven feedback. This approach enables personalized care, remote monitoring, and predictive health insights to empower both patients and healthcare providers to make informed decisions that can lead to timely interventions and better health management.[1, 2] However, several challenges remain in the development of devices for smart health applications. Most of these devices rely on built-in batteries or frequent connections to external power sources for recharging, which often makes them bulky and rigid, ultimately leading to user discomfort during prolonged use.[3] Additionally, the limited lifespan of batteries necessitates frequent replacements, which can be particularly problematic for long-term monitoring and management. In the case of implantable devices, this often requires additional surgical interventions, which not only increases the risk of pain and infection but also places a significant burden on both patients and healthcare systems.

To address these challenges, flexible, self-powered, and low-maintenance alternatives offer smart health devices the potential to reduce or even eliminate their dependence on traditional batteries. Given that most smart health devices are in direct contact with the skin or internal organs, ensuring they are lightweight, flexible, and conformable significantly enhances user comfort. For the self-powered aspect, various available energy sources around the human body have been considered, including solar energy from ambient light, thermal energy from body heat, biological energy from physiological reactions, and biomechanical energy generated by human movements. Among these sources, biomechanical energy is particularly promising because it is continuously generated through natural movements such as walking, running, breathing, and heart beating during one's lifespan. This energy source is abundant, reliable, and capable of being harvested without the need for external power supplies, making it ideal for powering wearable and implantable health devices. By converting biomechanical energy into usable electrical energy, flexible biomechanical energy harvesting (BEH) can offer a sustainable and reliable power source while simultaneously ensuring user comfort and gathering vital information about movement and health from the human body. As a result, flexible BEH aligns closely with the needs of smart health, particularly in ensuring minimal maintenance and enhancing device autonomy.[4-8] The integration of flexible BEH with smart health technologies represents a pivotal advancement in modern healthcare, with the potential to transform the ecosystem of connected health monitoring, diagnostics, and data-driven care solutions.

Flexible BEH also encompasses several primary energy conversion methods, including the triboelectric effect, piezoelectric effect, and the hybridization of both. Triboelectric nanogenerators (TENGs) work on the principle of converting biomechanical energy into electrical energy through a combination of the triboelectric effect and electrostatic induction when two different materials repeatedly come into contact and then separate. TENGs are highly effective in harvesting low-frequency biomechanical movements, which shows great promise in friction-based smart health devices. For example, TENG-based wristbands can be used as wearable and

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portable electricity sources by harvesting energy from human motions when a conventional power supply for electronic devices is challenging in daily life.[9-11] They are promising power sources for long-term, continuous monitoring devices in patients who require ongoing assessment of their physical conditions. Since TENGs can generate electric signals from minimal movements, they are ideal for sensing applications. Some flexible TENG-based wristbands have been further developed for human-machine interaction (HMI) applications by controlling some electronic devices and computer operations, including thermometers, oximeters, and computer software [12, 13] Such wearables could also attach to the human arm for continuously monitoring various muscle indicators and creating an alert system for injury risk during daily exercises.[14] Furthermore, TENG technology is well-suited for health condition monitoring, providing valuable data for both preventive care and disease management, as demonstrated by the development of TENG-based flexible patches for detecting and diagnosing conditions like Parkinson's disease and hemiplegia.[15-17]

Another type of energy conversion method is through piezoelectric nanogenerators (PENGs), which also hold significant promise for smart health applications. They can convert mechanical stress or strain into electrical signals based on the piezoelectric effect, which is highly suitable for harvesting repetitive or subtle biomechanical motions from the human body. Therefore, PENGs can be integrated into wearable or implantable devices that monitor physical activity or health conditions, utilizing mechanical energy from daily activities to power sensors and other electronics. One compelling application of PENGs in smart health is in cardiac systems, where the subtle mechanical deformations caused by the beating heart can be harvested to power or supplement the power supply of biomedical devices such as pacemakers.[18-20] This approach ensures continuous, long-term operation of healthcare devices without external power sources, enhancing the reliability and convenience of cardiac-based care. PENGs can also detect human motion and physiological activities, wirelessly transmitting data to remote host electronics for continuous, real-time healthcare monitoring.[21] In addition, PENGs can be embedded into shoe insoles or socks to harvest biomechanical energy from each step, enabling the tracking of physical activity levels and gait patterns to assess overall mobility.[22-24] This is particularly beneficial for elderly individuals or patients undergoing fall detection, disease diagnosis, and gait correction, as the system can provide real-time feedback on their movement patterns without relying on batteries or frequent recharging.

To optimize energy collection, flexible BEH devices can combine multiple energy conversion methods, such as PENGs and TENGs, to create hybrid energy harvesting systems. These systems enhance the efficiency and reliability of energy harvesting in smart health applications, ensuring that devices can operate continuously under various conditions. By integrating different energy sources, hybrid systems can maximize energy output while accommodating the diverse needs of health monitoring devices.[25-27] Additionally, electromagnetic generators (EMGs) are being combined with TENGs or PENGs for applications involving larger movements, such as walking energy harvesting and healthcare monitoring.

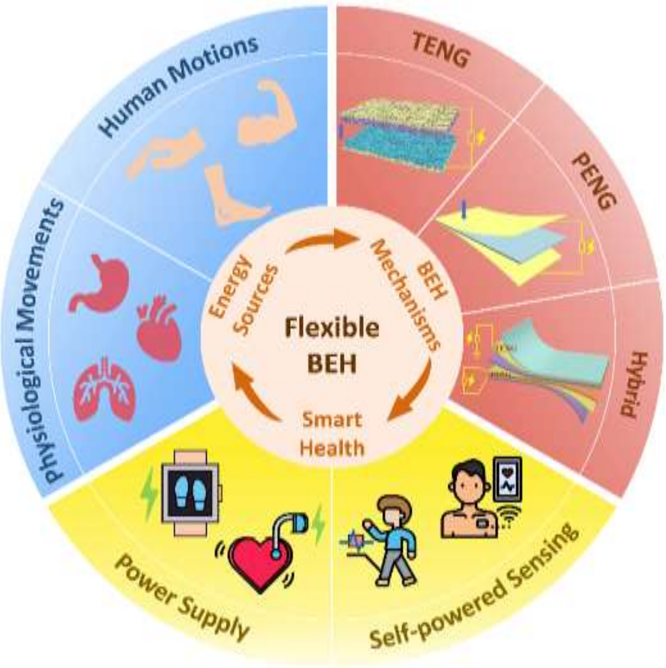


Fig. 1 A schematic overview of the flexible BEH approach, categorizing energy sources, energy harvesting strategies, and their applications in smart health.

There have been numerous published reviews on BEH, focusing on energy harvesting technologies,[28-32] material and structural configurations,[5, 33-35] and biomechanical applications.[8, 36-39] By contrast, this review distinguishes itself by providing a comprehensive overview of biomechanical energy sources and harvesting strategies tailored specifically for sustainable, self-powered healthcare technologies. It aims to bridge the gap between energy generation principles and their practical integration into healthcare devices. By systematically addressing biomechanical energy sources, flexible BEH methods, and their applications in self-powered sensing and sustainable power supplies for health devices, this review provides unique insights into how flexible BEH can enable continuous, real-time health monitoring and sustainable power solutions, particularly in smart health innovations (Fig. 1). It explores energy source-based design strategies that enhance the adaptability and efficiency of BEH systems while improving compatibility with wearable and implantable designs. Additionally, this review underscores the synergy between flexible BEH technologies and emerging healthcare paradigms, making it a practical guide for researchers aiming to translate BEH technologies into clinical and commercial applications. Ultimately, this holistic approach sets it apart from existing research that primarily focuses on standalone energy mechanisms.

2. Biomechanical Energy Sources

The advancement of low-power electronics in healthcare the multi-functionalization and miniaturization of wearable and implantable devices. However, maintaining a continuous and stable power supply remains a significant challenge. This has driven researchers to explore alternative solutions, with energy harvesting technologies emerging as a promising approach to address this issue. Harvesting biomechanical energy from the human body has been a topic of great interest for more than 100 years since the first hand-cranked generator was proposed to consciously convert mechanical energy into electrical energy.[40] The human body serves as a tremendous storehouse of biomechanical energy, which can be harnessed from daily movements and physiological activities to power various electronic devices. This energy harvesting approach holds considerable potential for developing sustainable power solutions for future wearable and implantable technologies in medical-related applications. To power wearable devices, energy from the motions of the limbs, head, and feet striking the ground can be harvested from the human body. For powering implantable devices, energy from the motion of the beating heart and the expansion of the lungs during breathing can be harvested internally. By employing various energy harvesting techniques, the ambient or essentially “free” energy generated from the human body can be directly converted into electrical energy to power electronics that are used across numerous applications. Especially for biomedical applications, BEH can power wearable or implantable biomedical electronics in situ to act as self-powered biophysiological sensors or to extend the lifespan of existing medical devices, such as pacemakers.[21, 36, 41]

Based on the sources of energy, this review classifies biomechanical energy from the human body into two main categories: human motions and physiological movements. Fig. 2 presents the classification of biomechanical energy sources and the power generated from different regions of the human body.[42-51] It illustrates that various body movements can produce different levels of energy, which can be harvested by BEH devices for power generation and self-powered sensing. Motions that occur external to the human body can provide a rich source of biomechanical energy via specific movements or actions from the limbs, feet, joints, etc., and these physical activities are usually performed consciously due to the coordination of muscles, bones, and joints within the individual.[52, 53] Examples of human motions include walking, running, bending joints, and lifting objects, which produce significant and harvestable biomechanical energy for powering small wearable electronics or for self-powered sensing. Specifically, areas such as the feet, elbow creases, and kneecaps produce enough force or deformation for various types of energy harvesters to easily translate those motions into useable energy. For example, Ahmed et al. introduced a diamond-structured fabric-based flexible triboelectric sensing device and integrated it into an insole for monitoring gait patterns, walking speed, and fall detection of patients diagnosed with Parkinson’s disease.[54] Even subtle movements such as finger muscle contractions, facial expression changes, throat movement during talking or swallowing, and eye blinking generate mechanical energy that can be captured and utilized for further use. We have conducted some significant research in the field of energy harvesting from the human body, and particularly in the area of HMI, our group developed flexible piezoelectric sensors that could harvest energy from the flexion of multiple finger joints and subtle muscle movements in the arm to enable effective and self-powered control of robotic prosthetic hands.[55]

The other type of motion is physiological movements, which refer to the biological activities that transpire due to the natural processes within the human body. These movements are essential for life and represent a continuous source of biomechanical energy due to their repetitive and unceasing nature. Organs like the heart, lung, diaphragm, and stomach produce reliable energy harvesting sources owing to their infinite and inexhaustible locomotion during one’s lifetime. These movements usually occur without conscious effort, including heartbeat, respiration, digestion, blood flow, and more. For example, the rhythmic contractions and relaxations of the heart muscles generate pressure and endlessly pump blood throughout the body, while the expansion and contraction of the lungs during respiration facilitate the constant exchange of oxygen and carbon dioxide. Furthermore, digestive motility involves the continuous movement of the stomach and intestines to break down food and transport nutrients. Similarly, the circulatory system's constant movement of blood throughout the arteries and veins generates a pulsative flow to ensure the delivery of nutrients and oxygen to various tissues and organs. Energy harvesters can thus be developed and safely implanted near the specific organ to take advantage of the physiological motions that occur endlessly throughout one’s lifetime. For example, our group designed a piezoelectric energy harvester employing a helical

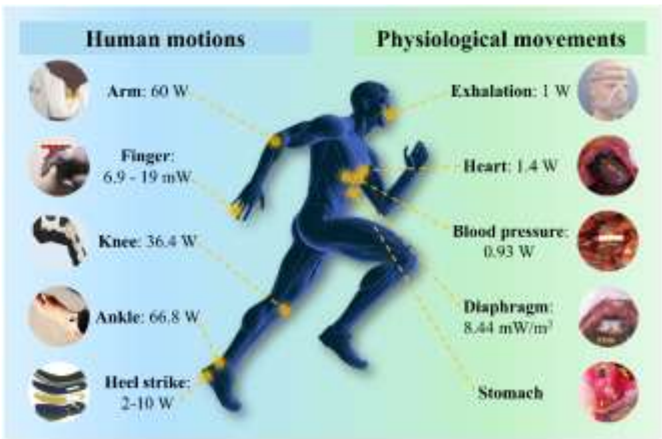


Fig. 2 Various sources of biomechanical energy from different regions of the human body: human motions (left) and physiological movements (right). Reproduced with the permission of ref.[42], copyright 2023, Elsevier. Reproduced with the permission of ref.[43], copyright 2022, Elsevier. Reproduced with the permission of ref.[44], copyright 2024, Wiley. Reproduced with the permission of ref.[45], copyright 2021, Wiley. Reproduced with the permission of ref.[46], copyright 2022, Wiley. Reproduced with the permission of ref.[47], copyright 2024, Elsevier. Reproduced with the permission of ref.[48], copyright 2010, Wiley. Reproduced with the permission of ref.[49], copyright 2024, Wiley. Reproduced with the permission of ref.[50], copyright 2014, Wiley. Reproduced with the permission of ref.[51], copyright 2018, Springer Nature.

design, which was seamlessly integrated with an existing implantable cardiac medical device (ICMD) by wrapping around the leads of a flexible pacemaker to harvest the continuous contractile movements of the heart muscles.[18] By optimizing the design of the piezoelectric-based energy harvester, it had the potential to extend the lifetime of the pacemaker's battery by more than two years, thereby minimizing the number of invasive surgeries needed to replace the depleted batteries of the ICMD. This demonstrates the potential of physiological energy harvesting to transform the longevity and sustainability of implantable medical devices.

Given the two categories of motions, body movements generally operate at relatively low frequencies, typically below tens of Hertz, with motion amplitudes in millimeters to centimeters scale.[56] Generally, biomechanical energy harvested from human motions such as walking and arm swinging is characterized by high output power despite being non-periodic and occurring in multiple directions. For instance, finger motions can generate between 6.9 and 19 mW of power, while more substantial movements like arm motion produce a significantly higher output of around 60 W.[57] Additionally, the walking cycle consists of the heel strike and coordinated movement of the ankles, knees, and hips, with biomechanical energy for each gait component evaluated to be 2-10 W, 66.8 W, 36.4 W, and 38 W respectively.[52]

In contrast, the biomechanical energy generated by internal organs, such as the heartbeat and lung movements, are continuous but yield low output power. Specifically, the heart and blood pressure generate approximately 1.4 W and 0.93 W respectively, while exhalation generates around 1 W of power.[57, 58] This provides the potential for long-term and sustainable power supply for implantable electronics or self-powered sensing. By harnessing these diverse sources of biomechanical energy, it is possible to sustainably power various portable or implantable electronics and develop self-powered sensors. This approach promotes more efficient and sustainable energy use and reduces reliance on traditional power sources. Overall, the human body's continuous activity, whether through human motions or physiological movements, ensures a steady and reliable supply of biomechanical energy, highlighting its potential as a sustainable energy source.

3. Biomechanical Energy Harvesting Strategies

From the human body, BEH can convert the abundant source of mechanical energy into electrical energy, offering sustainable and convenient solutions for powering wearable or implantable flexible medical devices and sensors in smart health applications. Based on their working principles, BEH technologies are typically categorized into triboelectric, piezoelectric, electromagnetic, and hybrid energy harvesting. Among these mechanisms, certain technologies have shown greater promise for practical BEH applications. For example, triboelectric and piezoelectric energy harvesting technologies are widely used due to their ability to harness energy from a broad energy source, extensive material options, simple structure, and ease of fabrication. Furthermore, the hybrid approach has garnered significant interest for its potential to maximize biomechanical energy captured from the human body by integrating various technologies. Although EMGs can also collect energy based on electromagnetic induction, they are not commonly used alone in BEH due to their bulky structure and mechanical complexity, making it difficult to integrate with flexible wearable devices and thus limiting their effectiveness and practicality. However, the high power output of EMGs continues to attract researchers who are exploring ways to combine them with other mechanisms for BEH applications. Thus, this paper primarily focuses on the various methods of piezoelectric, triboelectric, and hybrid energy harvesting methods.

3.1 Triboelectric Energy Harvesting

The triboelectric effect is referred as the charge transfer between two materials resulting from frictional contact, enabling the objects to carry equal and opposite charges.[59] When two dissimilar materials are subjected to contact, there is charge transfer between them due to the difference of electron affinity. Consequently, the materials tending to donate electrons get positively charged while the materials that accept electrons become negatively charged. The magnitude of charge generated during friction is significantly influenced by the relative electron affinity of the two materials. To comprehend the relative electron affinity capability among triboelectric materials, researchers have proposed a qualitative triboelectric series based on the nature of materials for obtaining or losing electrons.[60-63] Zou et al. quantitatively standardized the triboelectric series of various materials by measuring the triboelectric charge density with respect to a liquid metal.[64] According to Zou's research, materials farther apart in the series are paired together to generate more charges when rubbed against each other, and the sign of the triboelectric charges can be qualitatively estimated according to the relative position of the two materials in the triboelectric series. Furthermore, electrostatic induction is the process by which a nearby charged object causes the redistribution of charges within a conductor without direct contact. Therefore, when conductive electrodes are attached to or placed near the triboelectric materials, charge redistribution can be induced in the electrodes by the triboelectric charges generated on the materials.

By coupling the triboelectric effect and electrostatic induction, TENGs have been developed for converting ambient mechanical motions into electric energy.[65, 66] Based on the direction of the polarization change and electrode configuration, four fundamental working modes of the TENG have been proposed, defined as (i) contact-separation mode, (ii) lateral-sliding mode, (iii) single-electrode mode, and (iv) freestanding triboelectric-layer mode, as presented in Fig. 3a.[67, 68] The contact-separation mode involves two materials repeatedly contacting and separating from each other. When the materials touch, charge transfer occurs due to the triboelectric effect. As they separate, an electric potential difference is created between two electrodes, causing electrons

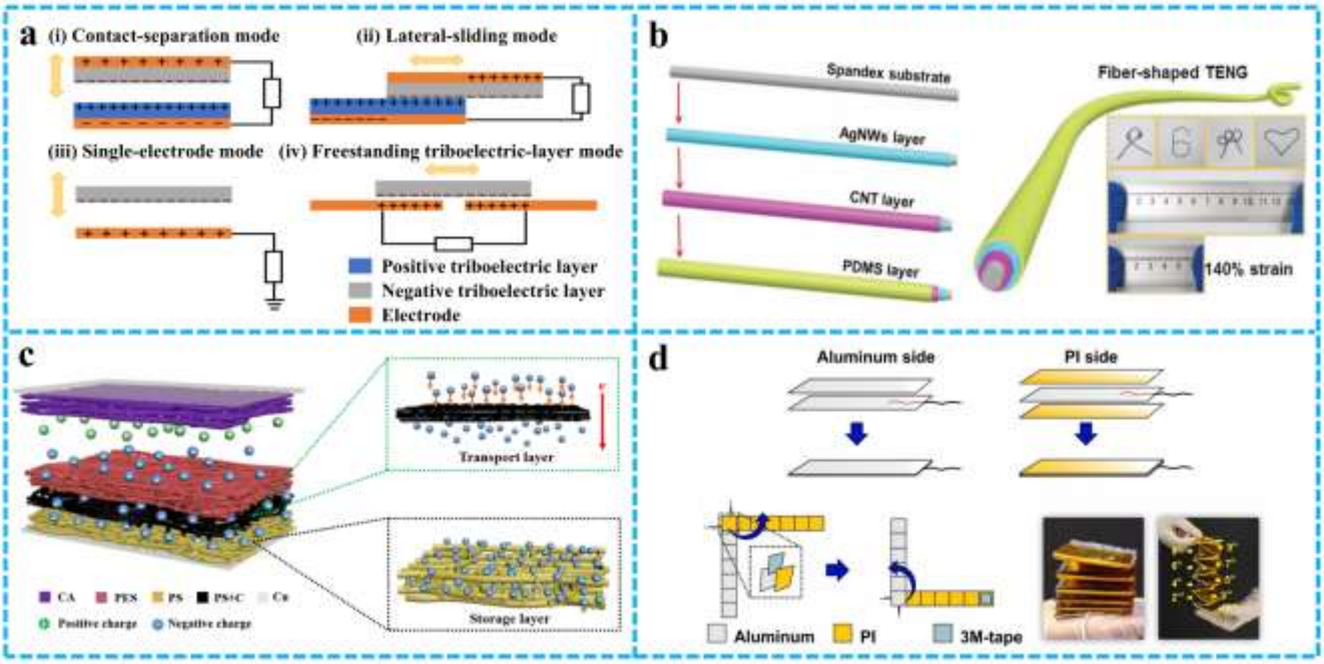


Fig. 3 Working mechanisms and structural designs of TENGs. (a) Four fundamental working modes of TENGs. (b) A flexible and stretchable fiber-shaped 1D TENG. Reproduced with the permission of ref.[87], copyright 2021, Wiley. (c) A multilayered 2D TENG that incorporates both charge transport and storage layers. Reproduced with the permission of ref.[90], copyright 2018, Elsevier. (d) A lightweight and highly efficient 3D origami TENG. Reproduced with the permission of ref.[95], copyright 2021, Elsevier.

to flow through an external circuit to balance the charge difference and generate an electric current. Similarly, in the lateral-sliding mode, the sliding motion between materials results in continuous contact and separation, creating an alternating electric potential difference that drives current through an external circuit. In the single-electrode mode, only one electrode is used to connect to an external circuit (usually the ground), which generates current as the electrons move to restore charge equilibrium under the effect of the potential difference. Lastly, the freestanding triboelectric-layer mode features a triboelectric layer that is free to move and induces a potential difference between two electrodes. Considering the versatility of biomechanical energy sources, the various working modes of TENGs offer multiple options for BEH applications. Additionally, TENGs possess advantages such as simple fabrication and integration, wide material availability, high performance, compact size, light weight, and low cost, making them particularly promising in the field of BEH.

3.1.1 Material selection of TENG. In designing flexible TENGs for BEH applications, selecting appropriate materials is essential for optimizing performance, durability, stability, and biocompatibility with the human body. Based on the functionality of the BEH device, the materials used in TENGs can be classified into triboelectric layer, electrode, substrate, and encapsulation materials. Triboelectric layer materials directly generate charges through the triboelectric effect, significantly determining the TENG's overall output. High-performance materials can be selected or created based on the triboelectric series, surface engineering processing, and hybrid or composite structure. For example, choosing materials far apart in the triboelectric series can enhance charge generation. Surface engineering techniques, such as nanopatterning and surface functionalization achieved by physical or chemical processes, and porous structure formation in triboelectric materials are commonly employed to improve the triboelectric properties of materials. Furthermore, hybrid or composite structures that combine diverse materials or multiple triboelectric layers can also enhance the triboelectric performance through synergistic effects. Common electron acceptor materials include polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), fluorinated ethylene propylene (FEP), and polyimide (PI), which are widely used as the negative triboelectric materials in the design of TENGs due to their strong electron affinity. Conversely, polyamide (PA), polyurethane (PU), skin, and some metal materials such as aluminum (Al) and copper (Cu) are often employed as electron donor materials. For example, PTFE tape has been utilized as the negative triboelectric layer in a milk-based paper TENG for harvesting energy from human body motion, with enhanced performance achieved through sandpaper processing to increase surface roughness and triboelectric performance.[69] As a positive triboelectric material, PA film exhibited better electrical output in a silicon rubber-based TENG fabric than PMMA, rubber, skin, and PTFE materials.[70] Different triboelectric combinations yield varying outputs due to their different electron affinities. Even when using the same triboelectric material, the polarity of surface charges can differ depending on its pairing.

Electrodes with high electrical conductivity are also crucial for efficiently collecting and transferring electrical charges generated by the triboelectric effect. For applications in BEH, electrodes in TENGs need to be flexible, biocompatible, and durable to conform to body movements, meet safety requirements, and perform well in complex environments. Pure metal materials such as gold (Au), silver (Ag), Cu, and Al are commonly used in TENGs due to their high conductivity and robustness, but specific designs like strips, wires, patterns, and metal-coated fabric structures are required in some wearable BEH cases to ensure the functionality. Notably, metal materials can be utilized in combination with other materials to serve as both the electrodes and triboelectric functions due to their high conductivity and excellent electron-donating ability.[71, 72] Additionally, metallic nanowires, nanosheets, and nanoparticles with enhanced surface areas such as silver nanowires (AgNWs) and metallic oxides such as indium tin oxide (ITO) are often used to prepare conductive electrodes in TENGs due to their high electrical conductivity and flexibility.[73, 74] Liquid metals like eutectic gallium-indium have excellent metallic conductivity, room temperature flowability, and softness, which are promising electrode materials for BEH applications.[75] Furthermore, carbon-based electrode materials like graphene, graphene oxide (GO), carbon nanotubes (CNTs), and MXenes can offer a good balance of conductivity and flexibility, which are good choices for flexible conductive electrodes.[76-79] Conductive polymers have the merits of solution processability, tailorable solubility, and high flexibility, allowing them to be processed into various forms including fibers, films, and textiles. Thus, conductive polymers like polyaniline (PANI) and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) have received significant attention in wearable TENG applications.[80-82] Composite conductive materials can integrate various types of materials to enhance the overall performance and functionality of the electrodes by leveraging the strengths of each component.[83, 84] While a variety of electrode materials offer diverse options to meet the specific requirements of different BEH applications, with each type of electrodes having its advantages, some limitations such as oxidation, corrosion, toxicity, and high costs need to be considered and addressed in practical BEH applications.

In some cases, structural support and robust protection from harsh external environments are necessary to ensure the stable operation of BEH devices. To achieve this, substrate materials and encapsulation materials are often incorporated in the fabrication of flexible TENGs. For example, Fan et al. utilized natural goatskin weaved by collagen fibers as the substrate material to construct an ultra-tough hydrogel, which was further fabricated into a stretchable single-electrode TENG for BEH applications.[85] Chen et al. created a stretchable and waterproof TENG and utilized the elastomer PDMS as the encapsulation layer to protect the device from environmental humidity.[86] Furthermore, dielectric polymers like PDMS, PU, polyethylene terephthalate (PET), PI, and ecoflex are widely used as both the substrate and encapsulation layers in TENGs due to their flexibility, stability, biocompatibility, and ease of fabrication. In summary, material selection is critical in designing flexible TENGs for BEH applications as it directly affects output performance and sensitivity. By carefully selecting and optimizing the substrate and encapsulation materials, TENGs can be effectively tailored for specific BEH applications, ensuring excellent durability, stability, and user comfort.

3.1.2 Structural designs of TENG. The structural configurations of TENGs play a crucial role in determining their energy harvesting efficiency and functionality. These configurations directly impact the amount of contact area, flexibility, and response to mechanical stimuli, all of which are essential for efficient BEH. Based on the dimensional structures of triboelectric layer and electrode materials, TENGs can be categorized into three different structural types: 1D, 2D, and 3D. 1D TENGs, often found as fibers or wires, hold significant potential for BEH applications, especially in wearable electronics, due to their ease of fabrication, simplicity of structure, good freedom and flexibility, and lightweight nature. Owing to their 1D structure, they can be easily integrated into textiles or woven into fabrics and conform to the human body well. In applications, 1D TENGs usually work in either the single-electrode or contact-separation mode because of their unique linear structure. For example, to monitor different human motions, Ning et al. fabricated a highly flexible and stretchable fiber-shaped single-electrode TENG with a coaxial structure through sequentially depositing conductive silver nanowires and carbon nanotubes and encapsulating PDMS onto stretchable spandex fibers (Fig. 3b).[87] Li et al. introduced core-sheath fiber-based flexible TENG for efficient BEH and comprehensive personal healthcare monitoring.[88] This design features helical nanocomposite polymer electrolytes (NPEs) coated conductive silver-plated nylon yarns encased in a PDMS sheath. Similarly, Ning et al. developed a helical fiber-based flexible strain sensor based on contact-separation mode TENG, featuring alternating PTFE/Ag and nylon/Ag braided fibers on a stretchable substrate fiber to detect respiratory movements and heartbeats.[89]

Despite their advantages, 1D TENGs exhibit a linear structure with limited contact area, resulting in lower power generation in capturing energy from complex, multi-directional movements, thus restricting their use in BEH. In contrast, 2D TENGs, typically composed of flat structures, overcome these limitations by offering a larger surface area to enhance power output. Their versatile design allows energy harvesting from diverse biomechanical motions, with multilayer planar films being the most commonly employed strategy in BEH applications. For example, Li et al. developed a multilayered wearable TENG with electrospun membranes that boost charge density through the charge transport and storage layers (Fig. 3c).[90] Similarly, Manchi et al. embedded $CaCu_3Ti_4O_{12}$ particles in PDMS to create a flexible TENG for BEH.[91] While large contact areas of 2D TENGs enable high power output, they also accelerate frictional wear on the triboelectric layers under repeated mechanical stress. Thus, enhancing durability is critical for 2D TENGs. Huang et al. addressed this by developing a snake-scale inspired keratin composite film based TENG with excellent resilience and durability.[92] Furthermore, environmental-friendly membrane materials have also been widely used in flexible 2D TENGs, as demonstrated by Feng et al. with a biodegradable bacterial cellulose-based TENG[93] and Chen et al. with a natural chitosan-silk fibroin-airlaid paper composite film.[94]

Unlike 2D TENGs, 3D TENGs operate in the transverse, longitudinal, and thickness directions simultaneously. They use complex geometries and volumetric structures to increase the contact area between the triboelectric layers, resulting in higher charge generation and improved energy conversion efficiency. 3D TENGs can also capture biomechanical energy from multiple directions to effectively convert complex biomechanical movements into electrical energy. One effective strategy for designing 3D geometries in TENGs is using origami technology, which can create complex, flexible, and deformable 3D structures from flat 2D substrate materials through various folding techniques. As shown in Fig. 3d, Pongampai et al. fabricated a lightweight, cost-effective, scalable, and highly efficient 3D TENG with a multilayer origami structure, powering 170 LEDs and driving an electric calculator through hand shaking.[95] Similarly, Tao et al. created a high-performance TENG with double-helix spring origami architecture, generating an open-circuit voltage of 1000 V from finger tapping.[96] Additionally, textile technology is employed to create 3D textile TENGs for flexibility and comfort, as seen in Dong et al.'s woven TENG with a peak power density of 263.36 mW/m^2.[97] Though 3D TENGs outperform 1D and 2D designs in BEH applications, their larger volume poses integration challenges for wearable flexible electronics.

3.2 Piezoelectric Energy Harvesting

The working mechanism of PENGs relies on the direct piezoelectric effect, which converts mechanical energy into electricity by generating electric charges in response to applied mechanical stress.[98] This process occurs due to the coupling between a material's stress state and its electrical polarization. The effect is reversible, as an applied electric field can induce strain in piezoelectric materials. Piezoelectricity arises from the non-centrosymmetric (i.e., no center of symmetry) of the material, which exhibits this effect when subjected to stain or stress, or when processed through techniques such as drawing and poling. This behavior is also observed in many biological materials, such as bone, tendon, skin, hair, wood, clamshell, amino acid, protein, and deoxyribonucleic acid.[99] In organic materials, piezoelectricity occurs through the reorientation of permanent molecular dipoles under mechanical stress, resulting in net polarization.[19] On the other hand, in inorganic materials, it is due to the asymmetric charge distribution in crystals that deform under stress.

Careful material selection is critical to optimizing energy conversion, durability, biocompatibility, and flexibility for PENGs. Ideal piezoelectric materials should have high electromechanical coupling factors, piezoelectric strain constants, and piezoelectric voltage constant values to enhance energy conversion efficiency.[100] Furthermore, flexibility and conformity are essential for devices that require direct contact with the skin or organs to ensure consistent performance and comfort. As previously discussed in our group's published work, biocompatibility is crucial to avoid immune reactions, with non-toxic and biodegradable materials offering added safety.[101] Additionally, in BEH applications, materials must be durable enough to withstand constant deformation from human motion. As material properties significantly impact device performance, selecting the appropriate piezoelectric materials is essential for practical applications. This paper focuses on the most commonly used piezoelectric materials for BEH applications, categorizing them by composition into three main groups: organic piezoelectric polymers, inorganic lead-based piezoelectric materials, and inorganic lead-free piezoelectric materials.

3.2.1 Organic piezoelectric polymers. Piezoelectric polymers are materials that exhibit piezoelectric behavior, which are found in several polymer families including fluoropolymers, polyureas, polyamides, polypeptides, polysaccharides, and polyesters.[102] Despite the relatively low piezoelectric coefficients, the intrinsic flexibility, lightweight nature, ease of fabrication, chemical stability, and biocompatibility of piezoelectric polymers make them highly suitable for wearable and implantable BEH applications. In addition, the growing demand for biodegradable devices has driven the development of biodegradable piezoelectric polymers in implantable BEH applications. These devices are designed to eventually degrade, ensuring the sustained well-being of the individual and eliminating the need for removal after their temporary effective lifespan. For example, biodegradable poly(L-lactic) (PLA) and glycine (Gly) have been combined to fabricate a flexible piezoelectric film for self-powered physiological signal monitoring.[103] Its biodegradability makes it promising for fabricating implantable biomedical devices to monitor physiological signals inside the body.

Among various piezoelectric polymers, ferroelectric poly(vinylidene fluoride) (PVDF) and its copolymer poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) stand out in BEH applications due to their excellent flexibility, ease of processibility, and chemical stability. The crystal structure of these polymers comprises five distinct crystalline phases, namely α, β, γ, δ, and ε phases, in which the piezoelectric property is attributed to the polar β, γ, and δ phases.[104] The β phase, with its all-trans chain structure, offers the highest dipole moment and the largest piezoelectric coefficient. Thus, increasing the β-phase content of these piezoelectric polymers can significantly enhance the electrical output of PENGs. Various processing techniques, such as mechanical stretching, high-temperature annealing, electrical poling, and filler incorporation, are able to induce dipole alignment for increasing the proportion of the β phase content, thus enhancing piezoelectric performance.[105] Despite the aforementioned advantages, relatively low piezoelectric coefficients of PVDF (d_{31} = ~ 20 pC/N and d_{33} = ~ -20 to -33 pC/N) and P(VDF-TrFE) (d_{31} = ~ -25 pC/N and d_{33} = ~ -30 to -40 pC/N) still pose challenges in achieving effective energy harvesting and sensing.

Piezoelectric polymers can be synthesized and processed using various fabrication techniques. For example, spin coating is widely used in microfabrication to create thin films, and it involves depositing a polymer solution into the center of a substrate and spinning it at high speeds to form a thin, uniform film (Fig. 4a).[106] Additionally, introducing micro/nano structures to PVDF films through phase-separation methods enhances compressibility and surface area-to-volume ratio, thus boosting piezoelectric efficiency.[107] For example, a water vapor phase separation method can create porous structures within spin-coated PVDF and P(VDF-TrFE) films, improving compressibility and charge collection, and thereby significantly increasing piezoelectric outputs compared to solid films.[107, 108] Recently, our group developed porous P(VDF-TrFE) films by combining spin coating with water vapor separation techniques, resulting in enhanced flexibility, sensitivity, compressibility, and permeability (Fig. 4b).[55] This improved piezoelectric polymeric material was utilized to develop a piezoelectric sensor for self-powered HMI.

Another effective fabrication method for piezoelectric polymers is electrospinning, a simple and versatile method that produces nanofibers with controllable diameters (Fig. 4c).[109] Without the need for post-processing, electrospinning naturally involves in situ poling and mechanical stretching, yielding crystalline electroactive phases like the β-phase in PVDF.[110] Inspired by jute fibers and tree bark, our group fabricated textured P(VDF-TrFE) nanofibers with interior porous structures and wrinkled surface morphology by combining the vapor-induced phase separation mechanism and electrospinning technique (Fig. 4d).[109] The resultant textured nanofiber-based device exhibited a well-rounded performance in power output, stretchability, toughness, and permeability. Specifically, the engineered textured structures of the nanofibers enhanced compressibility and expanded the surface area of the nanofibers, thereby demonstrating significantly improved piezoelectric performance with more than two-fold electrical generation. The textured devices not only harvested biomechanical energy from human movements but also demonstrated sensing capability for monitoring biophysiological signals. Additionally, 3D printing techniques, including direct ink writing and fused filament fabrication, can employ a layer upon layer processing procedure using piezoelectric polymers to enable the fabrication of PENGs with high efficiency while boosting piezoelectric performance.[111, 112] These fabrication techniques contribute to the development of high-performance piezoelectric polymers, enhancing their applications in energy harvesting and sensing technologies through continued innovation in material processing.

3.2.2 Inorganic lead-based piezoelectric materials. Inorganic piezoelectric materials are known for their excellent piezoelectric properties but face some limitations such as poor moldability, insolubility in organic solvents, limited size, and high brittleness.[113] Bulk piezoelectric inorganics are brittle and can fracture under minor strains, making them unsuitable for wearable and implantable applications. Integrating these materials into a flexible matrix or fabricating them into flexible structures, such as thin films, provides a strategy to address this challenge. Based on structural and morphological differences, inorganic lead-based piezoelectric materials can be categorized into lead-based ceramics and lead-based single crystals. For piezoelectric lead-based ceramics, lead zirconate titanate ($PbZr_{1-x}Ti_xO_3$, PZT) was the first studied of its kind and has subsequently become the mainstream due to its desirable elastic, dielectric, piezoelectric, pyroelectric, and ferroelectric properties.[114] PZT is a solid solution of $PbTiO_3$ and $PbZrO_3$ compounds that feature a high electromechanical coupling coefficient and a piezoelectric coefficient (d_{33}) ranging from approximately 300 to 1,000 pC/N, making it ideal for applications that require high sensitivity and efficient energy conversion.[115]

Thin films are a widely used form of PZT in BEH applications to overcome the brittle nature of this material, and various techniques have been developed for their fabrication, such as the sol-gel method, hydrothermal method, and sputtering method.[116] Among these techniques, the sol-gel method has been extensively utilized due to its numerous advantages, including low cost, precise control over thickness and composition, a short fabrication cycle, and uniformity over large areas. Wang et al. introduced a cost-effective sol-gel technique for fabricating large-scale, lightweight, and fully inorganic flexible PENGs based on PZT thin films and flexible 2D mica substrates.[117] Due to the versatility of PZT, it can be used not only as a thin film, but also as particles incorporated into various substrates like polymers, which enhances stretchability and mitigates toxicity issues related to lead. For instance, Huang et al. synthesized PZT ceramic particles by sintering a modified sol-gel solution and embedding them in a styrene ethylene butylene styrene (SEBS) elastomer substrate.[118] Due to the effective package of PZT particles by SEBS, the device demonstrated a high elasticity of about 950%, as well as biocompatibility through the cytotoxicity test.

Additionally, relaxor–$PbTiO_3$ (PT) single crystals have garnered significant attention in recent decades for their notable advantages, such as ease of growth near morphotropic phase boundary (MPB) compositions and superior piezoelectric properties through domain engineering.[119] For instance, (1-x)$Pb(Mg_{1/3}Nb_{2/3})O_3$–$x$$PbTiO_3$ (PMN–PT) and (1-x)$Pb(Zn_{1/3}Nb_{2/3})O_3$–$x$$PbTiO_3$ (PZN–PT) single crystals are solid solutions of lead-based complex relaxor perovskites with PT. With compositions near the MPB between rhombohedral and tetragonal phases, PMN–PT and PZN–PT single crystals exhibit the strongest piezoelectric effect, characterized by an electromechanical coupling factor (k_{33}) exceeding 90% and an ultrahigh piezoelectric coefficient (d_{33}) of ~ 2,500 pC/N, three times that of PZT ceramics.[120] Common methods for growing piezoelectric single crystals in BEH-related applications include solid-state crystal growth (SSCG) and modified Bridgman technique. SSCG enables the transformation of polycrystalline ceramics into single crystals through abnormal grain growth, offering cost-effectiveness, chemical homogeneity, and versatility.[121] Hwang et al. adopted SSCG and optimized delamination to create a flexible (011) single-crystalline $Pb(Mg_{1/3}Nb_{2/3})O_3$-$Pb(Zr,Ti)O_3$ (PMN–PZT) thin film (Fig. 4e).[122] The modified Bridgman technique, based on directional

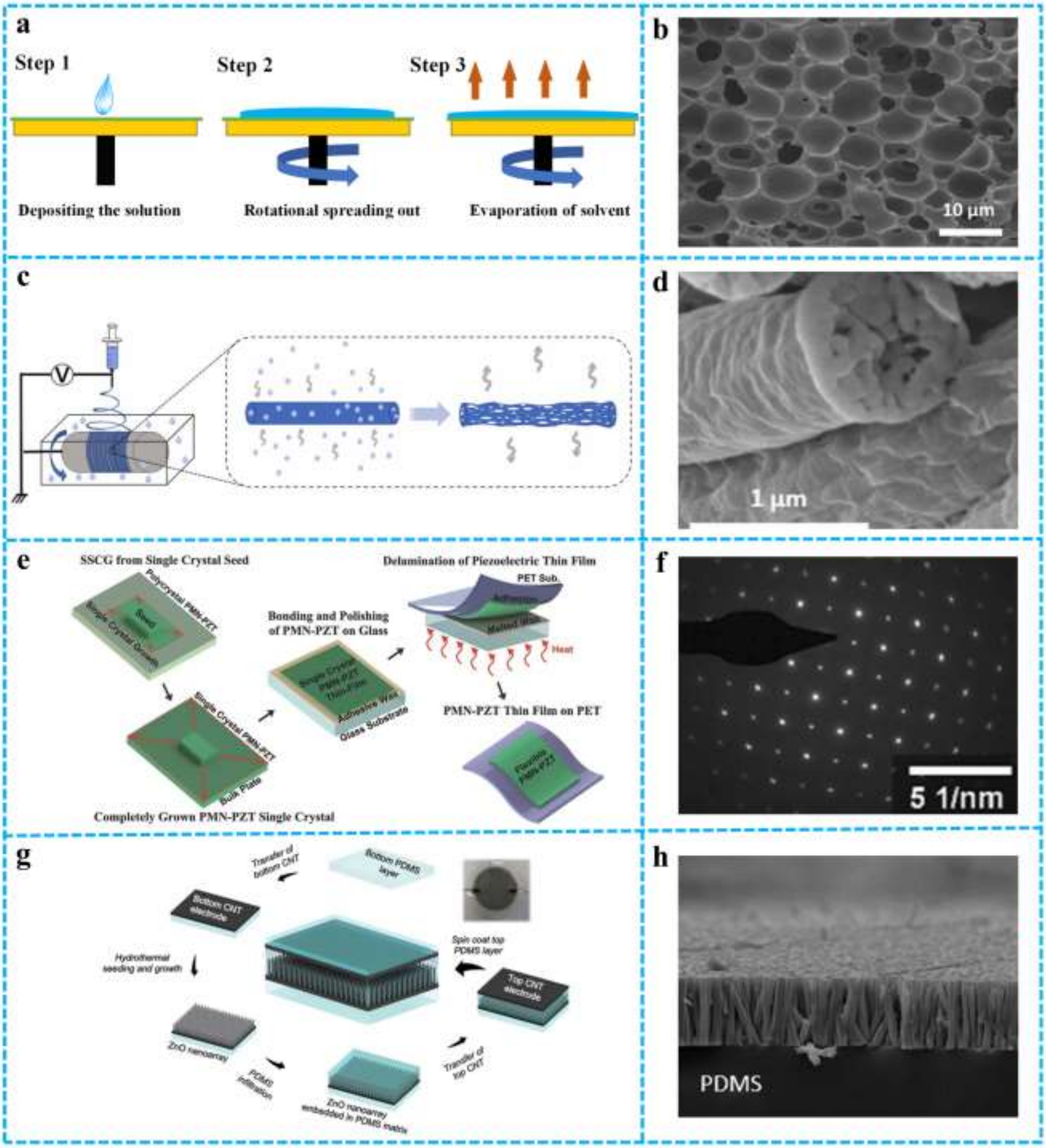


Fig. 4 Piezoelectric materials and their fabrication methods in PENGs. (a) A schematic of the spin coating method. Reproduced with the permission of ref.[106], copyright 2022, MDPI. (b) SEM image of a porous P(VDF-TrFE) film. Reproduced with the permission of ref.[55], copyright 2024, Wiley. (c) A schematic of the electrospinning method. (d) SEM image of textured P(VDF-TrFE) nanofibers. Reproduced with the permission of ref.[109], copyright 2024, Elsevier. (e) A schematic of the SSCG method to grow PMN–PZT single crystals. Reproduced with the permission of ref.[122], copyright 2015, Wiley. (f) The selected area electron diffraction pattern of PIN–PMN–PT single crystals. Reproduced with the permission of ref.[123], copyright 2024, Elsevier. (g) A schematic of the hydrothermal method to grow ZnO nanowires. (h) SEM image of vertically aligned ZnO nanowires. Reproduced with the permission of ref.[133], copyright 2021, Wiley.

solidification by translating a melt from the high-temperature zone to the low-temperature zone, was used to fabricate $Pb(In_{1/2}Nb_{1/2})O_3$–$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PIN–PMN–PT) single crystals with an exceptional piezoelectric charge constant d_{33} up to 2700 pC/N (Fig. 4f).[123] Nanoscale fabrication techniques, such as hydrothermal synthesis, have also been explored. Moorthy et al. fabricated a flexible PENG device, featuring 0.65PMN–0.35PT nanowires synthesized by the hydrothermal method and a PDMS elastomeric matrix, which could be easily bent by human fingers.[124] Despite their exceptional electromechanical properties, inorganic lead-based piezoelectric materials face challenges in durability, fabrication, and especially biocompatibility due to health and environmental concerns related to their lead content.

3.2.3 Inorganic lead-free piezoelectric materials. Concerns over lead exposure from inorganic lead-based piezoelectric materials, which can harm nearly every organ system, have driven research into safer, lead-free inorganic materials for BEH applications. Inorganic lead-free piezoelectric materials generally have perovskite or wurtzite-type crystal structures. Perovskite types, like barium titanate (BTO) and potassium sodium niobate (KNN), offer higher piezoelectric properties but require poling due to their ferroelectric nature.[19] BTO, the first discovered lead-free piezoelectric ceramic, exhibits a relatively high Curie temperature of around 120 ℃ and a piezoelectric efficient (d_{33}) of about 190 pC/N.[125] Flexible PENGs using BTO/PDMS composites have been utilized as self-powered wearable sensors for human motion detection and tactile perception.[126, 127] For instance, Su et al. fabricated a flexible PENG film using porous 3D $0.82Ba(Ti_{0.89}Sn_{0.11})O_3$-$0.18(Ba_{0.7}Ca_{0.3})TiO_3$ (BTS-BCT) piezoelectric ceramics as fillers within a PDMS matrix, producing ~ 14 V from finger movements.[126] KNN-based ceramics, with piezoelectric coefficients of ~ 100-400 pC/N, are also promising substitutes to replace lead-based materials.[19] Zhang et al. enhanced the output performance of a flexible PENG by incorporating KNN ceramic particles (d_{33} = ~ 347 pC/N) in a layered distribution within the PDMS matrix.[20] The implantable PENG could safely capture biomechanical energy from the heartbeat to generate electricity for self-powered cardiac pacing.

Wurtzite-structured piezoelectric materials, such as zinc oxide (ZnO) and aluminum nitride (AlN), offer chemical stability and natural piezoelectricity due to atomic-scale polarization.[128] AlN, with a piezoelectric coefficient d_{33} of 5.5 pC/N, is compatible with the complementary metal-oxide-semiconductor (CMOS) manufacturing process and has been used in thin films and nanostructures for PENGs.[129] Natta et al. reported a flexible AlN-based sensor for monitoring larynx swallowing movements.[130] ZnO, another wurtzite material, is widely used in energy harvesting, especially in biomedical applications due to its biocompatibility and biosafety. Since the first study on ZnO nanostructure-based PENG was reported in 2006, it has gained significant attention in this field.[131] Most ZnO research has focused on using low-temperature (<100 °C) solution synthesis techniques, such as hydrothermal methods, to grow ZnO nanorods on flexible substrates.[132] The synthesis generally involves two steps: first depositing a seed layer onto a substrate and then growing ZnO nanorods on that seed layer. For instance, Jin et al. employed a hydrothermal method to grow ZnO nanowires directly on CNTs, embedding them in a PDMS matrix to create a highly flexible and biocompatible device that generated energy from finger motions and heartbeats (Fig. 4g, 4h).[133] Strategies to enhance ZnO-based PENGs output include doping, increasing nanorods areal density, surface treatment, interfacial modification, and combination techniques.[132] For example, doping ZnO with 5% Li increased the voltage output by nine times compared to the pure ZnO-P(VDF-TrFE) device.[134] Pratihar et al. combined multi-walled carbon nanotubes (MWCNTs) into flexible ZnO–PVDF composites, which reduced the compatibility issue and supported the homogeneous dispersion of ZnO nanorod fillers within the PVDF matrix.[135] Although inorganic lead-free piezoelectric materials are more biosafe, they generally exhibit lower piezoelectric coefficients and require more complex material synthesis processing methods, requiring careful consideration when choosing between lead-based or lead-free piezoelectric materials.

3.3 Summary of Various BEH Strategies

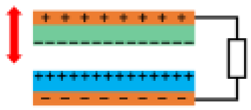
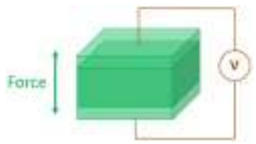
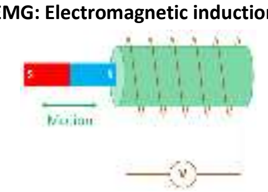
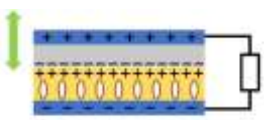
This section summarizes various energy harvesting strategies in BEH applications, detailed in Table 1. TENGs effectively capture biomechanical energy from the human body through the triboelectric effect and electrostatic induction. Their broad range of material options and diverse working modes enable efficient energy collection, generating high output voltage and power density from human body activities like vibrations, bending, pressing, and shaking based on contact-separation and single-electrode modes. Combined with their flexibility and lightweight design, this makes them well-suited for harvesting energy from the human body. However, simultaneously achieving high voltage, current, and power density remains challenging due to their inherently high impedance (at the level of MΩ) and relatively low energy conversion efficiency. Potential structural fatigue and the decline of conformability between different functional layers may also reduce the output durability of the device in BEH applications. As such, further research is needed to develop materials for TENG-based applications that can achieve an optimal balance of high triboelectric charge density, conductivity, biocompatibility, flexibility, stretchability, and comfort, as well as environmental stability and friendliness.

PENGs harvest mechanical energy from human body motions and convert it into electricity based on the direct piezoelectric effect with a variety of piezoelectric materials for construction. In BEH applications, the simple structures of PENGs allow for efficient energy conversion from bending, tapping, shaking, and vibration from human body motions. PENGs have the simplest structure compared to other mechanisms, where mechanical energy is directly converted into electrical energy without additional components. PENGs can generate relatively high power densities, making them ideal for harvesting biomechanical energy even on a small scale. Combined with their flexibility and stability, PENGs are also well suited for smart health applications. However, due to their high impedance typically exceeding 100 kΩ, PENGs can only generate low current outputs despite relatively high voltage outputs. Since piezoelectricity occurs only in certain materials, the selection of materials for PENGs is limited. Besides, the energy conversion efficiency of piezoelectric materials is further restricted by their intrinsic properties compared to other energy harvesting strategies. While PENGs can be scaled down to the nano- and microscale levels, they often face limitations in low current and power outputs, necessitating improvements through a multifaceted strategy incorporating material choice, structural designs, and fabrication techniques to enhance their performance.

Building on these advancements, various TENGs and PENGs have been developed to harvest biomechanical energy from the human body. However, the energy generated often falls short of the long-term power needs of electronic devices due to the low energy conversion efficiency of these technologies. Hybrid energy harvesting strategies that combine multiple energy harvesting methods can overcome these limitations, maximizing energy output and improving efficiency, reliability, versatility, and sustainability. Although effective, hybrid designs are complex, and literature on them is limited, so this section primarily focuses on integrating piezoelectric, triboelectric, and electromagnetic energy harvesting mechanisms. Triboelectric-piezoelectric hybrid is a common method for converting biomechanical energy into electrical energy, owing to their similar structures, matchable internal impedances, facile fabrication methods, and easy integration. In particular, layered planar hybrid TENG-PENG are extensively studied for their output performance and ease of fabrication and integration.[136, 137] This configuration not only combines the triboelectric and piezoelectric effects simultaneously but also maximizes contact areas between different triboelectric and piezoelectric materials, enhancing energy conversion efficiency. Despite their advantages, layered planar configurations of hybrid devices face several challenges, such as increased thickness affecting integration and comfort. To address these issues, 3D hybrid TENG-PENG was developed, as seen in Liu et al.'s 3D trinary-yarn-interlocked hybrid TENG-PENG and Li et al.'s 3D coaxial hybrid TENG-PENG.[138, 139] Overall, triboelectric-piezoelectric hybrid devices can yield higher voltage output and enhanced energy conversion efficiency.[25, 26] They also offer broad energy harvesting, versatile designs and applications, and improved reliability.

While piezoelectric and triboelectric techniques are the most widely used transduction mechanisms to convert biomechanical energy into electrical energy, other mechanisms can also be utilized. For example, EMGs use electromagnetic induction to generate electrical energy within a conductor in a changing magnetic field. For BEH applications, EMG-based devices can harvest energy from joint rotation, shaking, pressing, and vibration of the human body, converting biomechanical energy into electrical energy through relative movement between electrical conductors and magnets. While standalone EMGs are bulky, their high current and power output make them appealing for such applications, and so researchers have been actively exploring hybridizing triboelectric or piezoelectric mechanisms with EMGs to enhance the power output. Zhang et al. developed a hybrid TENG-EMG with double-layered acrylic substrates as the framework, separated by four springs, to efficiently harvest biomechanical energy from walking.[140] Further, Rodrigues et al. combined triboelectric, electromagnetic, and piezoelectric mechanisms in a sole for harvesting energy from walking, yielding a significant power output of 32 mW.[141] Wang et al. also designed a TENG-PENG-EMG hybridized device to harness biomechanical energy for powering wearable devices, demonstrating a substantial increase in output through a pulley-wheel-guided speed-enhanced system.[142]

Table 1 Summary and comparison of various energy harvesting strategies

BEH mechanisms	Advantages	Disadvantages
TENG: Triboelectric effect and electrostatic induction 	• Versatile material choices • Simple fabrication and multiple working modes • High voltage output and power density • Flexible, lightweight, and cost-effective • Scalable in micro- to macroscale	• High internal impedance (MΩ) • Low current (nA to µA), power (µW to mW), and conversion efficiency • Poor durability • High sensitivity to environmental factors (such as humidity and temperature)
PENG: Direct piezoelectric effect 	• Simple structure for direct conversion • Relatively high voltage output and power density • Flexible and relatively stable • Scalable in nano- to macroscale	• High impedance (>100 kΩ) and low current (µA to mA) • Limited selection of available materials • Limited energy conversion efficiency
EMG: Electromagnetic induction 	• Relatively high output current (mA) • Low output impedance (a few Ω to several kΩ) • Robust and durable operation	• Low efficiency in low frequencies and small size • Hard to integrate with electronics and microsystems • Not compatible with MRI
Hybrid TENG – PENG: Integration of the two mechanisms 	• Enhanced energy conversion efficiency and power • Broad energy sources and frequency bandwidth • Versatility in structure designs and applications • Improved durability and environment stability	• High internal impedance • Complexity in design and coupling

In summary, hybrid energy harvesting that combines piezoelectric and triboelectric methods leverages the strengths of PENGs and TENGs for improved power output and efficiency. This combination allows for energy harvesting across a broader range of mechanical stimuli and frequency bandwidth. Although hybrid devices enhance durability and stability by enabling simultaneous or separate operation of triboelectric and piezoelectric mechanisms, they still face challenges like high internal impedance, coupling, and complex design. Coupling PENGs and TENGs into a single hybrid device requires careful design considerations to ensure material compatibility, structural configuration, electrical output, and impedance matching. Recent studies have explored the hybridization of EMGs with TENGs or PENGs for BEH applications, aiming to achieve higher power output by leveraging their complementary characteristics. However, advancements in this area are limited due to the bulky and rigid nature of EMGs. Further advancements are needed to design more compact and flexible EMG units and integrate them more effectively with TENGs or PENGs, thereby expanding the application potential of these hybrid devices in BEH for smart health applications.

4. Biomechanical Energy Harvesting Applications

4.1 Biomechanical Energy Harvesting for Sustainable Power Supply

Conventional low-power wearable and implantable electronics for healthcare applications rely heavily on batteries, which disrupts continuous operation and reduces user convenience. Especially for implantable devices, battery replacements often necessitate invasive surgeries, posing additional health risks, particularly for patients with compromised health. To address these issues, researchers are exploring alternative power sources through energy harvesting technologies that can derive energy from the human body to create seamless, long-lasting, and safer flexible electronics for smart health applications.[143, 144] As a sustainable and accessible source of energy, biomechanical energy from the human body can be scavenged from various forms of motion and subsequently converted into electrical energy based on triboelectric, piezoelectric, and electromagnetic mechanisms, or through hybrid designs. This makes the BEH method ideal for powering low-energy and lightweight flexible biomedical devices, transforming how we integrate technology with the human body.

4.1.1 Harnessing energy from human motion. Biomechanical energy generated from human motions features easy acquisition, broad distribution, and significant amplitudes, making it an excellent power source for medical electronics. Joint movement is particularly valuable, as it plays a crucial role in daily activities such as walking, bending, and lifting, providing numerous opportunities for energy harvesting across various body positions. Recently, advancements have led to innovative energy harvesting devices designed to tap into biomechanical energy from joints. For example, Hou et al. developed a liquid metal-based single-electrode piezo-triboelectric hybrid nanogenerator to harvest finger bending energy, in which the $BaTiO_3$/rubber composite film served as the effective negative triboelectric material (Fig. 5a).[145] The piezoelectricity and enhanced permittivity of the $BaTiO_3$/rubber film resulted in a ~50% enhancement of output voltage and current. Varghese et al. fabricated a highly flexible TENG based on electrospun PVDF nanofibers with paper as the counter material, capable of harvesting energy from wrist flexion, elbow bending, and finger tapping to produce open-circuit voltages of 80, 120, and 160 V respectively.[146] Additionally, Wang et al. developed a stretchable and shape-adaptable liquid-based single-electrode TENG using potassium iodide and glycerol (KI-Gly) liquid electrolyte, which can be worn around the wrist, elbow, and knee to produce high peak-to-peak voltage of 6 V, 500 V, and 600 V respectively.[147]

Besides joint motion, harnessing energy from hand tapping presents an exciting opportunity to convert natural hand movements into electrical energy. For example, Xia et al. introduced a transparent and stretchable TENG based on edible grade silica gel and crystal mud, achieving 1400 V, 25.96 μA, and 150 nC at a pressing frequency of 5 Hz when covered by a nitrile glove.[148] Potu et al. developed a flexible film-based TENG consisting of PDMS and ZnO nanosheet films synthesized on a surface-modified aluminum substrate, which can generate a peak-to-peak output voltage, current, and power density of 1442 V, 155 μA and 10.8 W/m^2 with a hand tapping force of ~ 7 N.[149] Notably, the TENG can power 824 LEDs, a stopwatch, a calculator, and a digital watch without additional storage elements. In addition to TENGs, PENGs are also designed to capture energy from hand movements due to their simple structure and good stability. Lu et al. developed a high-performance flexible PENG, featuring a 3D nano calcium barium zirconate titanate (BCZT)@Ag heterostructure that harvests the hand-slapping energy to light up nine LEDs instantly with no external energy storage needed.[150] Similarly, Zhang et al. designed a flexible PENG using aligned P(VDF-TrFE) nanofibers and 3D interdigital electrodes, generating 130 V from finger pressing to directly drive 32 LEDs (Fig. 5b).[151]

Foot movements during walking, running, or jumping generate significant forces, thus offering abundant energy for BEH applications. Energy harvesting devices can be seamlessly integrated into various placements near the foot, such as within the shoes and on the insoles. For example, Zhao et al. attached a flexible TENG based on polyester conductive cloth to the heel of a slipper, generating 514 V and 27.6 μA to power 150 LEDs.[152] Hao et al. developed a foot-mounted TENG using L-cystine/nylon composite nanofibers, generating a power density of 11.52 W/m^2, and successfully powering a hygrothermograph, pedometer, and sport watch system (Fig. 5c).[153] Besides direct energy capture, Huynh et al. designed a hybrid TENG-EMG that was driven by the airflow resulting from the foot repeatedly compressing a bicycle pump, allowing LEDs and Internet of Things (IoT) sensors to be illuminated and powered at different input pressures.[154] Alves et al. also created a hybrid TENG-EMG that harvests energy from the foot-strike via a radial-flow turbine to power a pedometer.[155] PENGs can also yield considerable electrical outputs from foot movements, as demonstrated by Yadav et al., who fabricated a flexible nanofiber mat-based PENG using solid-state synthesized hexagonal boron nitride nanoflakes embedded in a PVDF matrix, generating ~98 V during walking to power electronic circuit or a pedometer.[156]

Energy can also be harvested from other body movements. Feng et al. integrated a wearable fabric-based TENG into clothing to scavenge biomechanical energy from arm swinging, producing 107.17 V by rubbing and 256.60 V by tapping to power an electrical watch (Fig. 5d).[157] Similarly, Zhao et al. developed a flexible single-electrode TENG mounted on a flame-retardant textile jacket, generating 200 V from arm movement.[158] Overall, human motion across numerous bodily positions presents a continuous and renewable energy source. Harvesting this energy offers a sustainable, cost-effective, and user-friendly power supply solution, in which this approach can reduce or even eliminate the reliance on conventional batteries, significantly enhancing the functionality, adaptability, and portability of wearable devices.

4.1.2 Powering devices with physiological movement. Biomechanical energy from physiological movements features periodicity, continuity, and small amplitudes, making it a highly promising energy source for implantable medical devices given

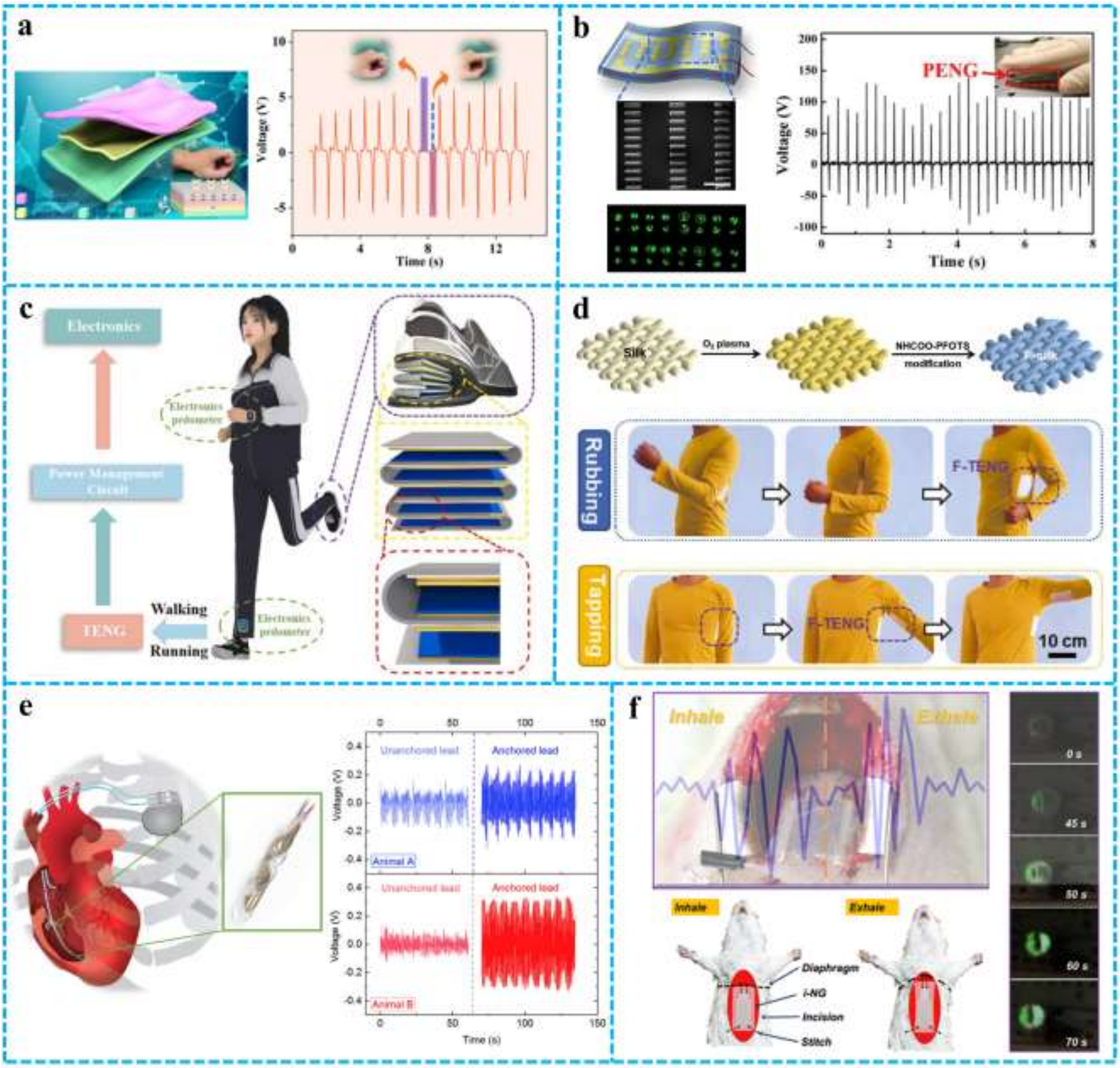


Fig. 5 Biomechanical energy harvesting from various motions. (a) A liquid metal-based piezo-triboelectric hybrid nanogenerator that harvests energy from the flexion of finger joints. Reproduced with the permission of ref.145, copyright 2022, Elsevier. (b) A flexible PENG with 3D interdigital electrodes for harvesting energy from various finger movements. Reproduced with the permission of ref.151, copyright 2019, Elsevier. (c) A foot mounted TENG for harvesting energy from foot-strikes on the ground. Reproduced with the permission of ref.153, copyright 2023, Elsevier. (d) A fabric-based TENG for harvesting energy from arm swinging. Reproduced with the permission of ref.157, copyright 2022, Elsevier. (e) A bio-inspired helical structured PENG wrapped around the pacemaker lead. Reproduced with the permission of ref.183, copyright 2019, Elsevier. (f) An ultra-stretchable implantable TENG for in vivo breath energy harvesting. Reproduced with the permission of ref.190, copyright

their low power requirements. Among these, cardiac energy harvesting is particularly promising for powering medical devices due to the rhythmic, powerful contractions of the heart, which provide a steady and reliable energy source. In particular, cardiovascular disease (CVD) is a significant medical problem as the leading cause of morbidity and mortality worldwide, accounting for nearly one-third of global deaths.[159] ICMDs can effectively manage arrhythmia in patients and also serve as interventional therapy for heart disease.[160] However, the limited battery capacity of these devices necessitates frequent replacement surgeries, which not only impose financial burdens but also cause pain and increase the risk of infection for patients. The heart itself is a significant in vivo biomechanical energy source that can provide sustainable power for ICMDs such as pacemakers through various energy harvesting methods.[20, 123, 161-164] One cardiac energy harvesting strategy is to attach flexible energy harvesting devices directly to the heart's surface to take advantage of the continuous myocardial contractions and relaxations. Several studies have been conducted to demonstrate energy harvesting from the heart's surface to power pacemakers. For example, Ouyang et al. demonstrated an implanted TENG-based symbiotic pacemaker (SPM) with PTFE and Al as the triboelectric layers, which achieved successful cardiac pacing and sinus arrhythmia correction on a large animal model.[161] The TENG generated an in vivo open-circuit voltage of up to 65.2 V with an energy output of 0.495 μJ per cardiac cycle, exceeding the required endocardial pacing threshold energy of 0.377 μJ. Zhang et al. constructed an all-in-one flexible PENG that harvested energy from canine cardiac pulsations, successfully storing energy in a commercial capacitor to stimulate the heart.[20] More recently, An et al. reported a high output flexible PENG adopting PIN–PMN–PT single crystals, producing a short-circuit current density of 3.08 $\mu A/mm^3$ and an open-circuit voltage of 1.8 V.[123]

From a structural design perspective, our group has developed various configurations using piezoelectric materials for energy harvesting applications, including cantilevers,[165-171] plates, patches and membranes,[48, 134, 161, 172-178] beams,[108, 179-182] and helical structures.[18, 183, 184] In cardiac energy harvesting applications, rather than maintaining direct contact with the heart, another promising strategy involves integrating flexible EH devices into the design of existing commercial or self-developed ICMDs to capture biomechanical energy from the beating heart. Dong et al. explored this approach by integrating flexible porous P(VDF-TrFE) based PENGs with the lead of pacemakers or implantable cardioverter defibrillators.[18, 108, 165, 183, 185, 186] This approach is compatible with current pacemaker lead implantation techniques, minimizing the need for additional surgeries that burden patients while also extending battery lifespan. For instance, they developed a PENG by integrating a flexible, porous P(VDF-TrFE) film with a buckled beam array structure that harnessed the bending energy of a pacemaker lead during the beating of the heart.[108] They further incorporated flexible porous P(VDF-TrFE) films within a dual-cantilever structure that wrapped around the pacemaker lead, with the ends acting as cantilevers.[165] They also employed a bioinspired self-wrapping helical structure design for the porous P(VDF-TrFE) films, allowing flexible integration with existing pacemaker leads, in which a single helical energy harvesting device generated a 0.65 V peak-to-peak voltage from the pig's heartbeats (Fig. 5e).[183]

To address complications related to leads and pockets in conventional transvenous pacemaker therapy, leadless pacemaker therapy has recently been introduced in clinical practice.[187] These capsule-shaped devices are implanted via a catheter and affixed to the endocardium to pace the heart as needed.[160] To tackle battery depletion while mitigating interference with internal electronics, Closson et al. developed an all-nanofiber-based flexible PENG to wrap around a leadless pacemaker using conductive poly(3,4-ethylenedioxythiophene) polystyrene sulfonate–poly(ethylene oxide) nanofiber electrode layers and a P(VDF-TrFE) active layer.[188] The device harvested energy from the surrounding heart tissue during systole, generating a peak-to-peak voltage of 60 mV when anchored into a swine's heart. Liu et al. also proposed a miniature, lightweight, self-powered intracardiac leadless pacemaker that utilized a freestanding mode-based TENG with polyformaldehyde pellets and PTFE film as triboelectric layers.[189] The implanted device generated an open-circuit voltage of 6.0 V and a short-circuit current of 0.2 μA, successfully providing 0.026 μJ per cardiac cycle.

Other physiological movements such as respiration and digestion have also been explored as sustainable power sources. Advancements in microelectronics have reduced the power requirements of implantable devices, enabling sufficient biomechanical energy to be harvested from these movements to power implantable devices, extend their lifespan, or provide direct electrical stimulation in therapeutic applications.[51, 190-192] To convert slow and discrete muscle movements from respiration into a continuous DC output in vivo, Li et al. developed an ultra-stretchable implantable TENG system (Fig. 5f).[190] Driven by the upward and downward movements of a rat's diaphragm during breathing, the device produced multiple voltage peaks with an amplitude of 0.8 V in a single respiratory cycle. Furthermore, Liu et al. proposed a flexible PENG capable of harvesting biomechanical energy from respiration to power an LED, ultimately activating optogenetic designer cells to produce therapeutic outputs for implantable blood glucose control.[191] Due to the relatively high risk of infection and potential electrical hazards associated with commercial diaphragm pacing devices, Zhong introduced a self-powered TENG-based diaphragm pacing system designed to harvest biomechanical energy from intercostal muscle contractions.[192] Subcutaneous implantation of the device in rats showed consistent amplitude over 4 weeks. To harness the continuous motion from digestive processes, Yao et al. developed a flexible and biocompatible vagus nerve stimulation (VNS) implantation system with a TENG attached to the surface of the stomach.[51] The TENG's Au leads connected to the vagus nerve, using stomach motion-generated voltage (0.05-0.12 V at 0.05-2.0 Hz) to reduce food intake for obesity treatment.

Overall, the exploration of BEH from physiological movements emphasizes its potential to power medical devices. Voltage output remains a critical performance factor for power supply, even though the power requirements of many implantable medical devices are in the range of microwatts to milliwatts. As shown in Fig. 6, various BEH devices can generate voltages ranging from millivolts to kilovolts, depending on the specific energy source.[20, 51, 123, 146-149, 151, 152, 156, 158, 161, 183, 190-193] For each category of motion, TENGs generally produce higher voltage outputs compared to PENGs under similar conditions, with the contact-separation and single-electrode modes being the most utilized. For instance, using single-electrode mode, TENGs can generate an open-circuit voltage of up to 1442 V from hand motions.[149] With relatively large amplitudes and high mechanical deformation during movement, human motions generally generate higher voltages than physiological movements, enabling the potential to power more electronic devices or high-power electronics. Although PENGs generate relatively low voltages, they are particularly well-suited for harvesting energy from small-scale motions, making them promising for physiological movement applications to power low-power medical electronics.

In addition to voltage output, flexibility and biocompatibility are also essential to ensure both comfort and safety, particularly since many BEH devices are in direct contact with the human body. To design flexible BEH devices, various strategies have been employed, such as adopting flexible materials and encapsulation using soft polymers like PDMS, PET, and ecoflex. Biocompatible materials including silicone rubber and PTFE provide both excellent biocompatibility and flexibility, making them widely utilized in BEH devices. In powering applications using TENGs, PTFE and PVDF are often used as negative triboelectric layer materials due to their high electron affinity. For PENGs, polymeric materials, such as PVDF and P(VDF-TrFE), are widely used because of their biocompatibility and flexibility. For instance, PENGs that incorporated porous P(VDF-TrFE) films and Au were designed to harvest biomechanical energy from heartbeats.[183] Additionally, lead-based inorganic piezoelectric materials like PZT and PMN–PT are also used by researchers for their high piezoelectric coefficients. For applications related to power supply for implantable devices, some BEH devices are designed to be miniaturized, lightweight, and encapsulated in biocompatible casings to ensure user comfort and safety.

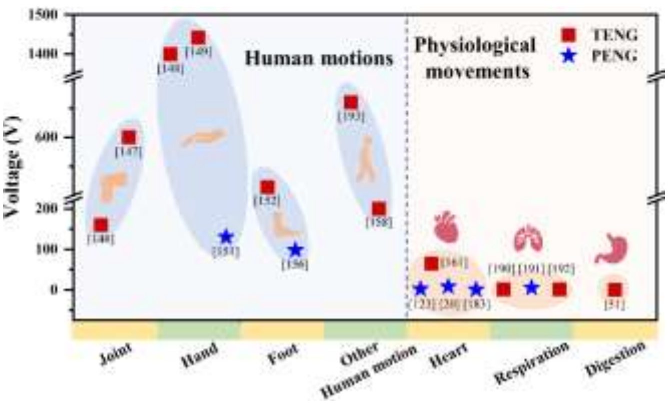


Fig.6 Comparison of reported BEH devices performance in terms of voltage output and body position for sustainable power supply applications.

4.2 Harvesting Biomechanical Energy for Self-powered Sensing

Self-powered wearable and implantable sensors represent a crucial technology in advancing personal electronics for smart health applications that can function sustainably and continuously without relying on external power sources.[194] The working mechanism of self-powered sensors aligns with energy harvesting, which can be accomplished through triboelectric, piezoelectric, electromagnetic, or hybrid mechanisms that convert biomechanical energy from various movements into electricity, thereby reflecting human physiological or behavioral characteristics.[195] The generated electrical signals can then be analyzed and utilized for real-time health monitoring, HMI, activity recognition, and more. Here, we also classify self-powered sensing into two categories based on the energy source: human movements and physiological movements.

4.2.1 Self-powered sensing from human motions. Biomechanical energy from human movements not only supplements power for low-powered flexible electronics but can also be harnessed for monitoring and interpreting numerous biophysiological processes through wearable sensors and data analytics. These technologies hold great promise in healthcare, rehabilitation, sports analysis, and HMI.[196-200] Joints such as the elbow, knee, finger, wrist, and shoulder play a crucial role in biomechanics, enabling various physical motions such as flexion and extension, abduction, and rotation during everyday activities. Recently, TENG-based sensors featuring wide sensing ranges, high sensitivities, and excellent conformability to the human body have been gaining significant attention. Kim et al. developed a stretchable TENG pressure sensor based on micropatterned fabric-coated MoS_2 and an ecoflex nanocomposite to detect joint motion with a high sensitivity of 17.18 V/kPa.[201] By integrating fish gelatin into polymer networks with in-situ formation of silver nanoparticles, Yan et al. developed a hydrogel-based TENG to sense finger and wrist bending, with a sensitivity of 0.205 V/kPa in the range of 0-605 Pa.[196] Niu et al. prepared a 3D bionic scale knitting TENG as a self-powered and wearable human-computer interactive sensing device that wirelessly interacted with phones through finger touches.[202]

To mitigate electromagnetic interference (EMI) from electronic devices, Zhu et al. developed a wearable TENG using cellulose nanofiber-based composite with high thermal conductivity and excellent EMI shielding performance.[203] This sensor provided real-time detection of human motions by analyzing output voltage peaks from the elbow, knee, finger, and wrist. In Fig. 7a, Xu et al. incorporated an ultra-thin ecoflex film and a flexible MXene/AgNWs decorated melamine foam into a TENG, achieving continuous, non-invasive joint monitoring with electromagnetic shielding.[204] In pursuit of lightweight, cost-effective, and self-powered sensors, Liu et al. utilized fused deposition modeling 3D printing technology to construct a self-powered wearable knee joint monitoring system based on a dual ratchet structure, which integrated TENGs and EMGs for achieving bidirectional 360° knee rotation sensing with an accuracy of up to 10°.[44] PENG-based sensors are also notable for their self-powered capabilities, lightweight design, durability, stability, and high sensitivity to mechanical stimuli. In Fig. 7b, Ham et al. developed a flexible PENG using lead-free piezoelectric KNN particles embedded in a P(VDF-TrFE) matrix to generate ~ 5 V and ~ 1 μA under bending deformations,[205] while Su et al.[126] and Zhang et al.[206] advanced tactile imitation and movement monitoring through voltage-triggered sensors.

Self-powered BEH sensors for foot movement monitoring purposes can be used to analyze gait patterns, providing data on various parameters such as step count, foot pressure distribution, stride length, walking speed, and more. To enhance the sensitivity and stability of yarn-woven gait sensing devices, Wang et al. developed coaxial P(VDF-TrFE) and poly(hexamethylene adipamide) (PA66)-based nanofibers to fabricate scalable plain-woven TENG textile sensors for real-time gait analysis.[83] These sensors exhibit ultra-high sensitivity (8.36 V/kPa), a low limit of detection (0.01 kPa), excellent breathability, as well as good anti-bacterial, anti-fouling, and washable properties, making them ideal for smart insoles for gait monitoring in diabetic patients. Rahman et al. fabricated a high-performance TENG based on a nanoporous cobalt oxide/silicone and MXene/silicone coated stretchable fabric, which can be integrated into the sole of a shoe to form an eight-sensor array for foot pressure tactile sensing and gait sensing.[43] Yang et al. established a honeycomb-shaped TENG with 3D printed thermoplastic polyurethane (TPU) as the frame and polybutylene adipate terephthalate and aluminum foil as friction layers to sense the walking speed from movement frequency.[207] Additionally, Du et al. developed an insole hybrid nanogenerator (IHN) based on a sandwich TENG and an arched

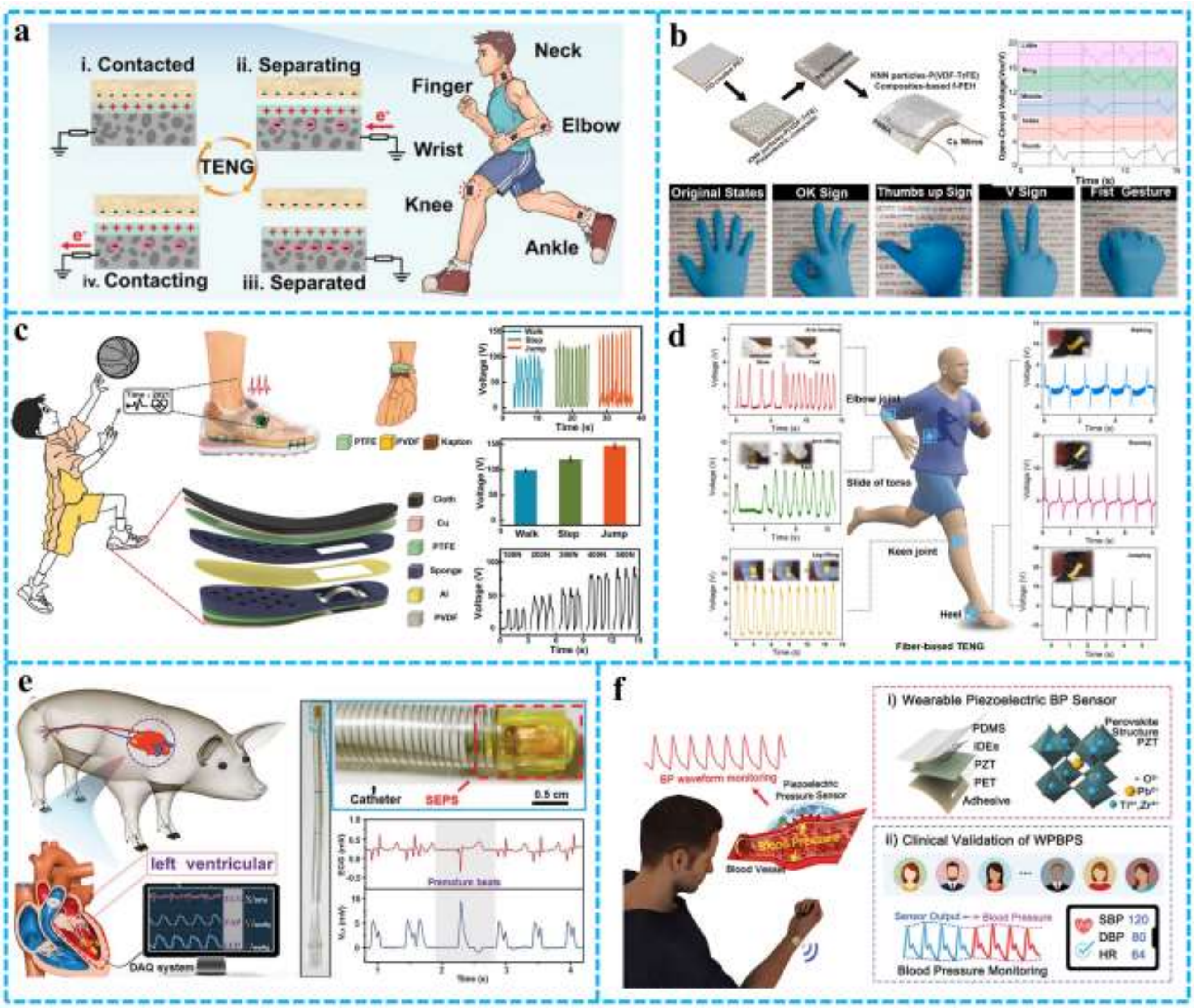


Fig. 7 Self-powered sensing from various motions. (a) A TENG sensor with EMI shielding performance for sensing various joint movements. Reproduced with the permission of ref. [204], copyright 2024, Wiley. (b) A composite-based flexible PENG for monitoring the angles of bent fingers and various hand gestures. Reproduced with the permission of ref. [205], copyright 2021, Elsevier. (c) A hybrid TENG-PENG sensor for gait monitoring and foot energy harvesting. Reproduced with the permission of ref. [46], copyright 2022, Wiley. (d) A fiber-based TENG for sensing the movement of elbow and knee joints, heel strikes on the ground, and the sliding of the torso. Reproduced with the permission of ref. [42], copyright 2023, Elsevier. (e) A flexible TENG-based endocardial pressure sensor implanted to the heart of a porcine model. Reproduced with the permission of ref. [214], copyright 2019, Wiley. (f) A wearable piezoelectric blood pressure sensor. Reproduced with the permission of ref. [219], copyright 2023, Wiley.

PENG design, capable of analyzing multiple gait types and collecting biomechanical energy from any form of foot locomotion (Fig. 7c).[46] A self-powered dorsalis pedis artery monitoring system based on an IHN, a PVDF pulse sensor, and an integrated circuit board was further developed to track the physiological state of athletes and patients with lower extremity arterial diseases for smart health monitoring. The pulse sensor converts the blood pressure vibration in the dorsal artery of the foot into electrical signals, while the IHN harvests pedal-generated energy to charge the lithium-ion batteries.

Human motion sensing goes beyond joint and foot movement monitoring to capture a wide range of body dynamics. Zheng et al. developed an all-textile TENG with a high sensitivity of 3.438 V/kPa, enabling pose correction in basketball shooting.[208] To enhance versatility, sensors were designed for multiple body locations. For example, Zheng et al. utilized the electrospinning and 3D printing processes to fabricate a hybrid TENG-PENG sensor that detects motion throughout the body,[209] and Abir et al. produced flexible TENG sensors from PVDF and gold-sputtered TPU nanofibers for sensing muscle contraction, opening and closing of the hand, finger motion, wrist rotation, and breathing.[210] Pratihar et al. doped high entropy oxide nanoparticles with PVDF to fabricate flexible PENG for detecting the movements of the finger and heel.[211] To achieve waste upcycling, Li et al. utilized natural porous materials derived from pomelo-peel biomass to develop a TENG for joint motion, neck movement, and gait pattern sensing while also powering LEDs and portable electronics.[212] To overcome the challenges of scalable fabrication and low conductivity in fiber-based electronics, Hao et al. developed a flexible, ultra-stretchable conductive TPU/MXene fiber coated with dopamine-modified MXene, enabling self-powered sensing of various movements (Fig. 7d).[42] Overall, human motion sensing facilitates continuous data collection and real-time feedback to enable improved monitoring of movement patterns, posture, and activity levels. This capability enhances smart wearables and allows automated systems to respond intuitively to user gestures and movements, ultimately improving user experience and interaction with technology.

4.2.2 Self-powered sensing from physiological movements. Rich biophysiological information, such as heart and respiratory rates, can be obtained from movement that stems from ongoing physiological processes.[213] In particular, various self-powered heart sensing devices have been developed to monitor endocardial pressure, heart rate, and cardiac contractility in situ due to the prevalence of CVDs worldwide.[18, 123, 214-216] For instance, Liu et al. presented a miniaturized, flexible, and self-power TENG-based endocardial pressure sensor with a sensitivity of 1.195 mV/mmHg, using PTFE film and Al foil as triboelectric layers (Fig. 7e).[214] When implanted into the heart, the sensor could detect the changes in endocardial pressure, as well as ventricular fibrillation and premature ventricular contraction. Furthermore, continuous monitoring and detection of abnormal changes in cardiac contractility could contribute to the early identification of potential CVDs. Qu et al. proposed an implantable, self-powered, bias-free cardiac monitoring capsule for in situ cardiac contractility monitoring.[215] This TENG-based sensor features miniaturized dimensions, high sensitivity, and high signal-to-noise ratio (42dB). After being implanted into a swine's right ventricle via catheter intervention, the device successfully detected changes in cardiac contractility, premature ventricular contraction, and ventricular tachyarrhythmia. Zhao et al. proposed an in-situ gap-generation means by vaporizing soaked distilled water to fabricate a no-spacer TENG.[216] When mounted onto a rat's heart, the device could accurately monitor the normal heartbeat and arrhythmia, with a heart rate measurement accuracy of up to 99.73%. Besides, Dong et al. integrated a multi-layered porous P(VDF-TrFE)-based PENG into existing pacemaker leads to enable self-powered sensing of the right ventricle pressure.[18] The PIN–PMN–PT flexible PENG developed by An et al. also demonstrated its capabilities for arrhythmia monitoring.[123]

Hemodynamic parameters also provide valuable information about the cardiovascular system, such as arterial status and cardiac function.[49] These signals can be captured through self-powered sensing driven by the arterial pulse.[49, 109, 217-219] For real-time and wireless monitoring of hemodynamics, Tang et al. presented an implantable PENG sensor-based vascular electronic system by using PVDF nanofibers wrapped around a pulsating artery and a growable polyurethane (PU) sheath bioinspired by the leaf sheath to avoid growth restraint.[49] Meng et al. developed a highly conformal Kirigami structure-inspired TENG pressure sensor for wireless cardiovascular monitoring using PTFE and PET as triboelectric layers.[217] Due to the enhanced conformability and improved sensitivity, the sensor can accurately capture pulse wave signals from various arterial sites on the body across a wide range of prestressing pressures (1.3–18.6 kPa) even with significant motion artifacts. To monitor pulse waves, Zhang et al. proposed a flexible TENG using CNT/PDMS microcolumns, capable of accurately detecting subtle physiological changes such as radial pulses and fingertip pulsations.[218] As shown in Fig. 7f, Min et al. reported a wearable piezoelectric blood pressure sensor using a PZT thin film and interdigitated electrodes.[219] By incorporating a PDMS passivation layer and a medical-grade adhesive layer, the sensor demonstrated a high normalized sensitivity of 0.062 kPa^{-1} and a rapid response time of 23 ms. Recently, Kwon et al. developed textured P(VDF-TrFE) nanofiber-based flexible sensors that are capable of real-time sensing of various biophysiological signals, including the radial pulse from the wrist and seismocardiogram signals from the chest.[109]

TENGs and PENGs can also be utilized to develop self-powered respiratory monitoring systems, enabling potential applications such as respiration behavior recognition, respiration rate and depth monitoring, and respiratory disease detection.[37, 220-222] For example, Vázquez-López et al. proposed a smart, low-cost face mask for respiratory monitoring based on an all-fabric TENG (AF-TENG) with high molecular weight polyethylene (UHMWPE) and cotton fabric as the negative and positive triboelectric layers respectively.[220] The respiration process induces the triboelectrification in AF-TENG, enabling its use as a breath sensor that wirelessly triggers an alert if breathing ceases for several minutes as in cases of apnea. In addition, Sasikumar et al. proposed a self-powered face mask based on a flexible PENG using a composite of hierarchically connected dysprosium tungstate nanoparticles with molybdenum disulfide nanosheets (DyW@MoS_2), which could distinguish between normal and fast breathing.[221] The PENG generated ~ 141 mV at ~ 90% humidity, confirming that water vapor from human breath would not interfere with breath monitoring. Zou et al. developed a stretchable, bionic respiratory hybrid TENG-PENG sensor inspired by the shark gill cleft structure, endowing it with anti-interference ability, good stability, and fatigue resistance under long-term testing.[222] The hybridized sensor could simultaneously monitor the respiratory rate and depth by detecting the changes in abdominal circumference or chest circumference.

Self-powered sensing driven by other physiological movements such as intestinal peristalsis and bladder activity has also been thoroughly investigated to provide critical biometrics besides cardiac and respiratory data.[223-225] Li et al. used nonwoven fabrics made from electrospun core/shell PLLA/Gly nanofibers to develop a flexible PENG sensor patch capable of detecting intestinal peristalsis.[223] Under artificial enema-induced colonic peristalsis in rats at a frequency of ~ 0.2 Hz, the device produced a stable peak-to-peak voltage of over 2 V. To monitor weak microscale intestinal motility in vivo, Cheng et al. developed an ultrasensitive, mechanically asymmetrical TENG by utilizing PDMS and PET films as the soft and hard substrates respectively.[224] The device features an ultrashort work distance of only a few micrometers and excellent anti-interference capability in the highly interferential in vivo environment. When attached to the duodenum of a rabbit, the TENG sensor precisely detected duodenal peristalsis at a frequency of around 0.32 Hz and could continuously monitor different peristaltic states. To detect the bladder's full state, Hassani et al. integrated a sponge-based TENG sensor with a bistable actuator, which was used to empty the bladder for patients suffering from underactive bladder syndrome.[225] The self-powered sensor could harvest biomechanical energy from bladder contractions and relaxations, thus detecting the fullness status of the bladder for actuator activation.

For self-powered sensing applications, sensitivity is crucial for the effectiveness of self-powered sensing devices in detecting, monitoring, and responding to biophysiological movements. The comparison of reported flexible BEH devices regarding their in vitro sensitivity and body positions is illustrated in Fig. 8.[43, 49, 83, 109, 201, 208, 211, 212, 214, 217, 219, 223] The sensitivity of BEH devices for self-powered sensing of human motions ranges between 0.664 and 17.18 V/kPa, whereas for physiological movements sensing, it spans a much broader range, from 0.0048 to 440 V/kPa. For BEH-powered sensing of human motions, TENGs are the most widely used due to their inherently high voltage output characteristics and ease of integration. For instance, TENGs for foot motion analysis exhibit a high sensitivity of 8.36 V/kPa and incorporate various materials, including P(VDF-TrFE), PA66, and stainless steel

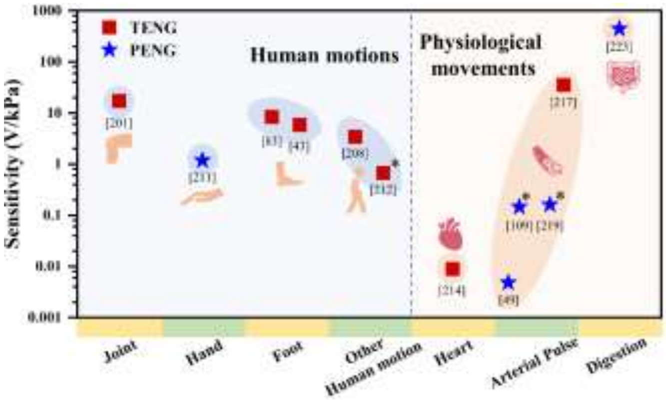


Fig. 8 Comparison of reported flexible BEH devices in terms of in vitro sensitivity and body position for self-powered sensing applications.

*Estimated date from the reference.

strands.[83] For arterial pulse monitoring, flexible TENGs and PENGs present high sensitivity and rapid response ability by using materials like PVDF, PTFE, and PZT. Notably, the sensitivity of PENG-based sensors can reach as high as 440 V/kPa for sensing applications pertaining to digestion, indicating it can even detect subtle pressure changes in the intestinal walls.[223] The differences between various biomechanical energy sources are also noted in Fig. 8, owing to the relatively consistent amplitude of human motion, whereas physiological movements exhibit greater variability in amplitude.

Sensors must also be safe for direct contact with skin or body tissues to prevent adverse reactions or allergies, making biocompatibility essential for health-based sensors. Flexibility, stretchability, and breathability are also important considerations, as they allow sensors to conform to the body contours while maintaining functionality and comfort during use. For instance, TENGs designed for joint motion detection demonstrate remarkable flexibility by employing materials such as ecoflex and P(VDF-TrFE). Lastly, durability and stability are critical factors as well for wearable and implantable sensors since they ensure a longer service life and stable operation in harsh environments. In applications related to physiological monitoring, such as heartbeat and respiration, devices utilize biocompatible materials like PDMS and PVDF to ensure stability and effectiveness over thousands of cycles.

5. Conclusions and Future Perspectives

This review provides a comprehensive overview of the most significant and relevant breakthroughs in the field of flexible BEH, focusing on biomechanical energy sources, BEH mechanisms, and their smart health applications. A wide range of BEH devices incorporating TENGs, PENGs, and hybrid mechanisms are gaining increasing attention for their flexibility and versatility in various smart health applications. Moreover, flexible BEH devices hold significant potential for harvesting energy from human motions and physiological movements to power wearable and implantable electronics, not only supplementing traditional power sources but also enabling self-powered biophysiological sensing for biometric analysis.

Despite the impressive advancements in this field, critical challenges remain to be addressed in the foreseeable future from the following aspects.

(1) Flexibility and user comfort: Ensuring sufficient flexibility and conformability is essential for BEH devices that come into direct contact with the skin or internal organs. Strategies such as incorporating soft polymers or designing stretchable structures can significantly enhance flexibility. For instance, integrating flexible substrate materials such as PDMS, PU, PI, and hydrogels can improve the flexibility of BEH devices. Stretchable structure designs, such as buckling, serpentine, helical, and Kirigami/Origami configurations, are particularly effective for integrating rigid and brittle inorganic materials. These structural designs absorb applied loads and strains, thereby enhancing both flexibility and stretchability.[226, 227] Moreover, woven textile designs provide another solution for designing flexible and stretchable BEH devices.

In developing devices that harvest biomechanical energy from human motions and physiological movements, the burdens associated with their use can increase metabolic costs, leading to physical fatigue, joint and muscle strain, cardiovascular stress, metabolic disorders, and other health issues. Ensuring user comfort is crucial to prevent BEH-powered smart health devices from interfering with daily activities or disrupting normal physiological functions. Therefore, user comfort is a key design consideration for BEH devices, and achieving a balance between user comfort and device performance remains a significant challenge. To address this challenge, solutions include minimizing the physical impact of BEH devices through streamlined, compact, and ergonomically shaped designs. Avoiding sharp edges and reducing bulk are necessary for preventing discomfort or injury, particularly in wearable and implantable applications.

Future advancements will focus on miniaturization and lightweight design, especially for BEH devices integrated with other electronics, to further reduce discomfort. One promising avenue for decreasing metabolic costs is energy harvesting from negative muscle work, such as in lower-limb devices around the knee joint. Moving forward, novel design strategies that balance comfort and functionality are critical. Flexible materials, ergonomic designs, and conformable systems that adapt to user movements will enable the development of unobtrusive, high-performance BEH devices for smart health applications.

(2) Biocompatibility and biodegradability: Wearable and implantable bioelectronics that utilize biomechanical energy as the input source require direct contact with human skin and various physiological systems for energy source proximity, enhanced sensing capabilities, and efficient energy transfer with minimal energy loss. Therefore, biocompatibility is a critical and mandatory criterion for BEH applications, especially in clinical settings and smart health applications. Regarding the user's safety and feasibility of long-term usage, it is essential to use biosafe materials that ensure safe and effective interaction with biological tissues. Currently, there are two main approaches to addressing this issue: employing all biocompatible materials or encapsulating the entire device with biocompatible materials. However, further challenges arise when focusing on the long-term biocompatibility of the materials, as most studies currently only assess short-term biocompatibility that are often limited to a week or so. Prolonging biosafety presents additional challenges that require extensive investigation, especially when integrating with existing implantable devices since meeting the regulatory standards can be a significant hurdle in the development of BEH devices. Furthermore, BEH-powered smart health devices involve the use of circuitry and electronic components for digitized health tools and advanced health applications. Thus, the design and long-term use of such devices with biocompatible materials require careful consideration so as to not hinder user comfort and safety while making direct contact with the body.

For the selection of biocompatibility tests associated with medical devices, the International Organization for Standardization (ISO) 10993 standards provide comprehensive guidelines.[228] These standards are widely recognized by major regulatory authorities, including the Food and Drug Administration (FDA) in the United States, the National Medical Products Administration (NMPA) in China, and the European Union (EU) for Conformité Européenne (CE) certification. Addressing the current standards and regulatory hurdles in clinical settings is crucial to bridge the gap between research innovations and real-world applications. Regulatory pathways often vary by region, with authorities such as the FDA requiring rigorous preclinical and clinical testing to ensure patient safety and efficacy, while the EU's Medical Device Regulation (MDR) imposes strict conformity assessments for CE certification. These processes can present significant challenges, including extended timelines, high costs, and the need for comprehensive documentation. For instance, biocompatibility testing must adhere not only to ISO 10993 standards but also to additional regional requirements, such as FDA's guidance on risk assessment and clinical evidence.

For medical devices that come into contact with intact skin, tests for cytotoxicity, irritation, and sensitization are generally required to verify the device biosafety on patients.[229] Moreover, for implantable devices, ensuring compliance with stringent regulatory expectations for sterilization, material durability, and long-term performance adds further complexity. These tests may include assessments for acute systemic toxicity, pyrogenicity, genotoxicity, implantation, and hemocompatibility to ensure safety and compatibility with the human body. Additionally, human clinical trials are required to validate the safety and efficacy of these devices in real-world scenarios, presenting another significant hurdle that demands robust study design, ethical approvals, and extensive data collection.

Alongside biocompatible considerations, the biodegradability of implantable devices is another critical factor for BEH applications. While not strictly required, with biodegradable implantations, there is a reduced need for surgery and the potential to lessen complication risks such as infection and inflammation, particularly for those with compromised health. Moreover, biodegradable devices align with the recent shift towards sustainability and eco-friendliness; no additional disposal procedures would be required since the device is designed to gradually degrade within the biological environment. However, balancing the full-scale integration of biodegradable materials while maintaining effective BEH presents challenges and necessitates ongoing experimentation in the choice of biosafe materials, material processing, and synthesis techniques to safely design materials with customizable degradation rates. Thus, the biocompatibility and biodegradability of BEH devices should be extensively evaluated and confirmed to ensure the biosafety of all materials and the user's continuous well-being.

(3) Power management: Smart health devices require efficient power usage, which must be addressed by optimizing conversion rates and device circuitry. Typically, both TENGs and PENGs generate relatively high voltages but with low currents and high internal impedances, as discussed in Section 3. Additionally, due to the irregular and fluctuating nature of human body movements, the electrical outputs of BEH devices are often transient and unstable. This makes them less compatible with direct use in many electronic devices or sensors without proper power management. One of the major challenges in effectively utilizing these devices is the need to convert their inconsistent output from human body movements into stable electricity that can be stored or directly used to power devices. Without adequate power management, energy loss due to impedance mismatch becomes significant, and the fluctuating output cannot meet the demands of consistent power delivery. While traditional power management systems consisting of rectifiers, impedance-matching resistors, and capacitors are effective in storing energy, they often struggle to meet the specific needs of advanced applications. To address these issues, researchers are developing sophisticated power management circuits that can optimize energy conversion efficiency by improving impedance matching, converting AC to DC, boosting current, and stabilizing the output voltage. These solutions aim to reduce energy loss and ensure consistent, reliable power delivery. Innovations in this area could include the integration of smart power management systems with adaptive control mechanisms that can dynamically adjust to varying inputs. Such advancements will be crucial for realizing the full potential of TENGs, PENGs, and hybridized devices particularly in powering next-generation wearable devices, medical sensors, and implantable smart technologies that require stable and efficient energy sources.

(4) Durability: TENGs and PENGs harvest biomechanical energy primarily through ongoing mechanical contact or deformation, which will lead to inevitable material fatigue, cracks, and surface wear over time. This is especially problematic for BEH devices used in smart health applications that require consistency. During long-term application, various active components of BEH devices may encounter risks of failure. For example, triboelectric or piezoelectric materials may deteriorate under repeated friction or mechanical stress. Additionally, the electrodes may become less effective due to wear or delamination after repeated deformation or cycling. Long-term exposure to environmental conditions like sweat and moisture can also result in deterioration or corrosion of the electrode materials, affecting their performance and durability.

To enhance longevity, BEH devices usually utilize encapsulation materials to protect against the effects of humidity, dust, chemical exposure, and other environmental factors. However, encapsulation materials themselves may experience failure under repeated mechanical stress, reducing their ability to protect the device's internal components. The mismatch of mechanical properties between different layered materials can cause delamination or stress concentration over time, affecting the overall durability of the device. Thus, careful material selection and design are crucial to ensure that they can withstand mechanical stress while maintaining their functions, thereby prolonging the lifespan and reliability of BEH devices in practical applications.

Advances in materials science, surface engineering, and structural design are key factors in overcoming the current challenges and realizing long-lasting, high-performance devices. For example, incorporating self-healing materials in constructing TENGs and PENGs can effectively enhance their lifespan by repairing microcracks and preventing the accumulation of mechanical damage. Developing new elastic or composite materials that offer enhanced mechanical resilience can increase the tolerance to mechanical deformation to ensure improved durability and flexibility for BEH devices. Modular designs, where individual active components can be replaced or repaired without affecting the entire system, can also effectively improve the long-term durability and maintenance of energy harvesters.

Moreover, surface engineering techniques such as texturing and protective coating can improve the charge density of TENG while minimizing wear and thus mitigating the effects of mechanical wear and environmental damage. Developing TENGs that do not rely on direct and continuous mechanical contact can drastically reduce wear and tear, leading to longer lifespans. Finally, developing hybrid energy harvesters that combine multiple mechanisms can mitigate the limitations of each technology. Overall, to ensure reliable operation over an extended period, BEH devices utilized in smart health applications must be robust enough to withstand repetitive motion, mechanical stress, and exposure to environmental factors.

(5) Stability: For smart health applications, the stability of flexible BEH electronics greatly depends on the surrounding environment. For wearable devices, high humidity or direct exposure to moisture can degrade the electric insulation of the functional components, leading to short circuiting or charge loss. Harsh humidity conditions can notably deteriorate the electron affinity of triboelectric layer materials, which lowers the energy output of TENGs. Long-term exposure to moisture may also cause corrosion of metal-based electrodes to affect the conductivity negatively. In addition, temperature fluctuations can also lead to changes in the mechanical stress of the materials, potentially causing expansion and contraction of the materials, delamination, and even fracture. In addition to humidity and temperature, dust from external environments may accumulate in mechanical joints, sliding surfaces, or between flexible layers of the active materials, thus obstructing motion or electrostatic induction.

For implantable devices, the complex and dynamic environment within the human body can also greatly affect the stability. For example, bodily fluids such as blood and interstitial fluid can be corrosive to materials within the energy harvester. The accumulation of biological material (e.g., proteins, cells, fibrous tissue) on the device surface can reduce the mechanical input for energy harvesting and consequently degrade the output performance. Additionally, electromagnetic radiation from nearby electronic devices or from the BEH device itself can interfere with the electrical circuits, leading to erratic behavior or reduced performance of flexible BEH devices. Careful consideration of environmental and biological factors is essential to maintain the stability of BEH electronics, which can be enhanced through careful material selection, adaptive structural designs, and protective encapsulation. Specifically, choosing or developing materials that are resistant to humidity and temperature can improve endurance and prevent material corrosion or degradation of the device. Materials with micro/nanostructured surfaces and self-cleaning functions can also be designed to repel water, dust, and biological contaminants. Furthermore, encapsulating or integrating the BEH device with functional coatings or protection layers, such as waterproof and anti-fouling coating, thermal insulation materials, and EMI shielding layers, can protect sensitive components from ambient environmental impacts. Thus, mechanical and electrical stability under varying conditions is crucial for the consistent performance of BEH devices in smart health applications.

(6) Integration of IoT Technology: Recently, there has been a significant shift towards more sophisticated, interconnected, and user-friendly devices in the IoT landscape for wearable and implantable technologies. That expands the applicability of devices that harvest biomechanical energy across various IoT-related applications, such as artificial intelligence (AI), HMI, virtual reality (VR), and integration of machine learning (ML) for healthcare monitoring and diagnostic purposes. With the inclusion of circuitry that enables such applications, it can lead to improved connectivity, wireless potentiality, and enhanced self-powered sensing capabilities in smart health applications. For example, real-time biophysiological data such as cardiac signals can be continuously collected even outside hospital settings for smart health monitoring to provide better health outcomes. Additionally, Bluetooth modules or near-field communication (NFC) technology enables the integration of wireless functionalities. For BEH-powered smart devices, AI- or ML-driven biometric analyses paired with wireless data acquisition can enable real-time and immediate decision-making in chronic disease management and critical care to provide instant alerts to healthcare providers.

Recent advancements have demonstrated the feasibility of integrating BEH devices with IoT technologies. For instance, prototypes of BEH-based wearables have been developed to monitor vital signs such as neck motion, sleeping breath pattern, pulse, voice, and gait.[230-232] The incorporation of AI algorithms enables BEH wearables to achieve real-time health data monitoring, predictive analytics, accurate interpretation, and personalized healthcare recommendations. The transformative potential of integrating BEH devices with IoT and AI ecosystems has enhanced healthcare options and advanced self-powered medical technology. A notable example is fabric-reinforced functional insoles that utilize triboelectric signals to track human movements while transmitting data wirelessly via Bluetooth to a smartphone.[233] Accurate locomotion recognition can be achieved by combining the sensing signals with machine learning algorithms based on 1D convolutional neural networks. Another pilot study demonstrates the application of an intelligent triboelectric sensing system for monitoring and providing early warnings of dry eye syndrome, where eye blinking can be detected with exceptional sensitivity, and the processed electrical signals can activate a coupled counter and transmit information to mobile devices through the IoT for automated processing.[234]

Despite the limitless potential in this area, significant challenges remain. Advanced technologies like ML and VR often require substantial computational power, which may exceed the energy harvested by BEH devices. Additional battery modules may be required to supplement the lacking power requirements, thus making the overall device bulky and more rigid. To address power limitations without bulky battery modules, it is essential to enhance the efficiency of energy harvesting methods to allow for a more streamlined and adaptable design. Furthermore, maintaining reliable, continuous data acquisition, especially wirelessly, even during periods of low movement or low power generation is critical for effective and long-term smart health monitoring. A good balance between data integrity and device functionality must be upheld through careful consideration of device design. However, combining various technological components into wearable or implantable devices can introduce design complexity, which would require innovations in miniaturization that do not compromise performance. This would also need to be balanced with maintaining user comfort and usability, considering that these devices are worn for extended periods of time. Additionally, the overall biocompatibility of the BEH device would need to be re-evaluated with added circuitry, especially when employed in a biological environment, as some materials may cause adverse reactions. Overall, addressing the challenges would require multidisciplinary approaches to integrate IoT capabilities with wearable and implantable electronics, thereby opening new horizons for BEH applications.

In summary, flexible BEH can drive advancements in the field of smart health by converting human motions and physiological movements into electrical energy to provide sustainable power supplies and enable self-powered sensing abilities for medical devices. For successful implementation, user comfort and biocompatibility are critical for long-term wear and maintaining the user's safety, preventing irritation or adverse biological reactions. Biodegradability is also desirable, complementing sustainable, eco-friendly development in wearable applications and eliminating the need for retrieval in implantable applications. Durability and stability are crucial for consistent performance under repeated stress and varying environmental conditions. Multi-source energy harvesting, combined with effective power management, holds promise to improve energy conversion efficiency and optimize energy utilization, thereby ensuring data integrity and maintaining device functionality. As BEH applications align with future technological developments, incorporating AI technology enables broader, smarter, and more responsive energy harvesting and sensing applications for smart health. Together, these considerations in materials science, power electronics, and computational techniques are driving the development of sustainable, user-friendly, and advanced BEH technologies for smart health electronics.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this feature article.

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Data availability statement

No primary research results, software or code have been included and no new data were generated or analyzed as part of this feature article.