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Review

Study on Human Motion Energy Harvesting Devices: A Review

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Abstract: With the increasing utilization of portable electronic devices and wearable technologies, the field of human motion energy harvesting has gained significant attention. These devices have the potential to efficiently convert the mechanical energy generated by human motion into electrical energy, enabling a continuous power supply for low-power devices. This paper provides an overview of the fundamental principles underlying various energy harvesting modes, including friction-based, electromagnetic, and piezoelectric mechanisms, and categorizes existing energy harvesting devices accordingly. Furthermore, this study conducts a comprehensive analysis of key techniques in energy harvesting, such as mode selection, efficiency enhancement, miniaturized design of devices, and evaluation of energy harvesting experiments. It also compares the distinct characteristics of different energy harvesting modes. Finally, the paper summarizes the challenges faced by these devices in terms of integrating human biomechanics, achieving higher energy harvesting efficiencies, facilitating micro-miniaturization, enabling composite designs, and exploring broader applications. Moreover, it offers insights into the future development of human motion energy harvesting technology, laying a theoretical framework and providing a reference for future research endeavors in this field.

Keywords: human motion energy; energy harvesting devices; piezoelectric; electromagnetic; friction

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1. Introduction

Wearable microelectronic devices have become increasingly indispensable in people's daily lives [1]. These devices play a crucial role in both civilian and military domains due to their miniature size, high performance, and exceptional precision [2]. Wireless technologies like Bluetooth, GPS (Global Positioning System), and sensing equipment have permeated diverse industries [3–5]. However, the battery capacity of microelectronic devices remains limited, resulting in restricted battery life [6,7]. This limitation hinders the ability to sustain long-term, high-intensity operations under existing energy technology conditions. Additionally, there are situations where it is not feasible to replace or recharge the power supply promptly. Moreover, traditional chemical batteries pose environmental risks. Consequently, one of the current areas of intense research involves the development and effective utilization of new power supply technologies [8–10].

In response to the limitations of traditional chemical batteries, numerous countries have conducted research and development on various environmentally friendly battery technologies since the last century [11–13]. As a result, traditional chemical batteries have been replaced in certain fields. However, challenges remain in terms of weight, volume, portability, and sustainability. In recent years, there has been a growing interest in utilizing micro-generators as an alternative power source in advanced fields such as aerospace, enabling weight reduction and improved efficiency [14–16]. This technology has gained significant attention and has become a hotspot of research [17]. Examples of micro-generation technologies include piezoelectric, electrostatic, electromagnetic, thermoelectric, wind power, solar energy, and triboelectric power generation [18–24]. These diverse micro-power generation technologies have opened up new opportunities in the field of human sports energy harvesting.

The human body plays a crucial role as an abundant source of energy, with its daily activities involving significant energy consumption and generation. Various bodily functions such as walking produce kinetic energy, exercise and sweating result in biomass energy, and the blood flow within the body, the beating of the heart, and the peristalsis of the digestive organs contribute to energy generation [25,26]. The majority of this energy is utilized for sustaining daily bodily activities. Consequently, there is a growing need for the development of simple and efficient energy harvesting devices capable of converting mechanical motions from different body parts into electrical energy [27–29]. From the perspective of human motion, the development of human energy harvesting devices mainly utilizes the following biomechanical energy: center of mass (COM) motion, joints motion, foot strike, and limb swing motion [30]. These devices can then power a wide range of wearable electronic devices, thereby extending their continuous working time [31–33]. Based on different energy harvesting principles, three primary types of devices are commonly employed: piezoelectric, friction-based, and electromagnetic devices [34–36]. Piezoelectric energy harvesting relies on the deformation of piezoelectric materials, which generates opposite charges on the corresponding surfaces through the coupling effect between the material's dielectric properties and elasticity. This process effectively converts mechanical motion into electrical energy output. Friction-based devices generate energy by creating friction between the human body-driven devices and other objects, thereby converting dispersive energy into electrical energy. The electromagnetic approach involves transforming human body motion into mechanical motion, causing a permanent magnet within the device to cut through magnetic sensing lines and generate electrical energy. Due to their simple structures, lightweight design, relatively high harvesting efficiency, and alignment with the requirements of sustainable development, these three types of energy harvesting devices are considered the primary methods for collecting human motion energy.

The efficiency goal of human energy harvesting devices is to minimize the user effort while obtaining sufficient electrical power. Michael Shepertycky and Qingguo Li proposed a new measure to describe efficiency [37], total cost of harvesting (TCOH), which is the ratio between the metabolic power increase from normal walking (without carrying the harvester) and the amount of electrical power produced. TCOH, which represents the additional metabolic power required to generate 1 W of electrical power in comparison with normal walking, considers both the cost of electrical power generation and the device carrying cost.

This paper summarizes the research progress of human energy harvesting devices based on three categories: friction-based type, electromagnetic type, and piezoelectric type. The practical applications, energy harvesting locations, and materials used for energy harvesting are introduced. Furthermore, the working principles, characteristics, and challenges associated with different energy exchange methods, as well as alternative approaches, are summarized. Moreover, the critical technologies of energy harvesting devices are analyzed in terms of their integration with biomechanics of human motion, enhancement of energy harvesting efficiency, and miniaturization of design. Finally, the future development of energy harvesting devices is discussed, including prospects for energy storage, efficient conversion, and more sophisticated energy harvesting methods.

This study places emphasis on analyzing the principle of energy capture, material application, structural design, and experimental evaluation methods of energy harvesting devices in different parts of the human body. It also conducts a comprehensive comparison of the advantages and disadvantages inherent in three types of energy harvesting devices. Additionally, corresponding optimization strategies are proposed. This study provides a theoretical framework and reference basis for follow-up research on the energy harvesting system and corresponding wearable electronic devices for different parts of the human body.

2. Development and Application of Triboelectric Nano Energy Generation Technology

The triboelectric nanogenerator (TENG) has emerged as a promising energy harvesting technology that can effectively convert distributed energy into electrical energy. It is widely used in various fields, such as wearable devices, biomedical equipment, the Internet of Things (IoT), and the natural environment [38–42]. By efficiently harnessing high entropy energy (dispersive energy sources such as kinetic energy, potential energy, thermal energy, electromagnetic radiation energy, etc.) from the surrounding environment, TENG represents a significant advancement in energy harvesting methods. Due to its unique size advantages, this technology can be operated on a smaller spatial scale, thus offering vast application prospects in numerous fields.

2.1. Fundamentals of Triboelectric Nanogenerator Technology

TENG's theory is the promotion of Maxwell's equations square. Academician Wang ZL, Chinese Acad Sci, Beijing Inst Nanoenergy & Nanosyst, added the "P_s" item to its equations which is used to explain the phenomenon of surface static charge polarization caused by mechanical contact. It is also called the "Wang" item [43,44].

$$J_D = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t} \tag{1}$$

TENG has the characteristics of inherent capacitors, and two capacitors are formed between its surface friction-charged electrical surface and two metal electrodes. The ratio of these capacitors varies according to the position of the electrical medium's surface, leading to electron transfer between the metal electrodes when short-circuited. This mechanism underlies the operation of TENG [45]. Based on the motion of the electrification layer and the configuration of the electrodes, TENG can be classified into four fundamental modes. Figure 1 illustrates the four basic working modes: vertical contact-separation mode, single-electrode mode, lateral sliding mode, and freestanding triboelectric-layer mode [46–49].

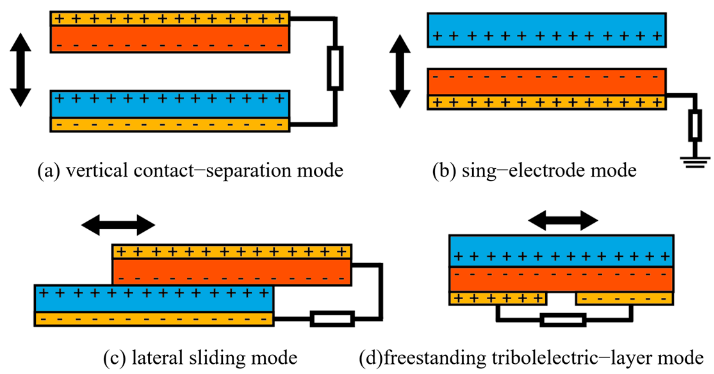


Figure 1. Four basic models of TENG [46].

TENG presents a promising solution for energy harvesting in human environments. As an emerging technology in this field, TENG has the potential to enable long-term use of microelectronic devices, with convenient portability and self-powered operation [49–51]. Subsequent research has further distinguished between internal and external energy harvesting based on the different sources of human energy. Corresponding energy harvesting devices have been designed using various energy generated by human motions, as illustrated in Figure 2.

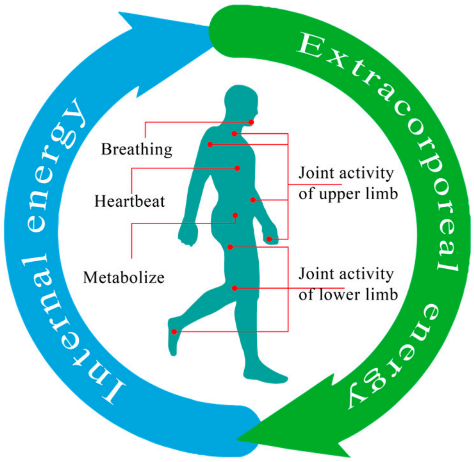


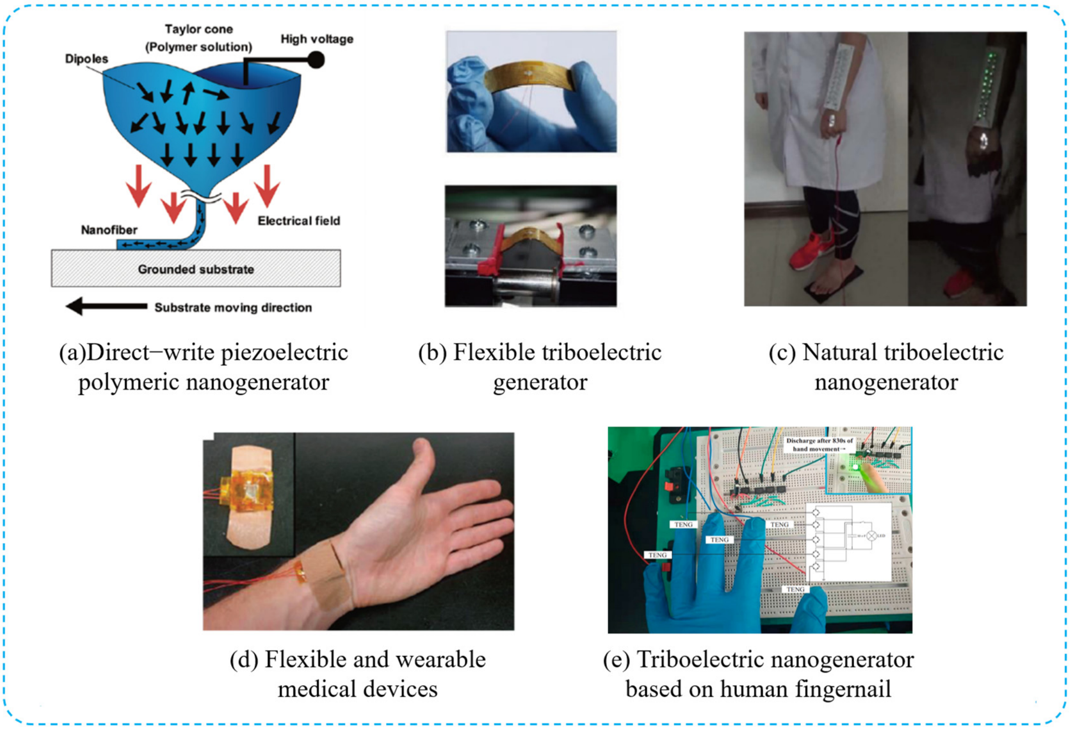
Figure 2. Environmental energy harvesting of TENG [52–61].

2.2. Trial Production and Application of Triboelectric Nanogenerator

TENG devices are commonly fabricated in the form of fabrics, with the dielectric properties of the materials serving as their core characteristic. These energy harvesting devices offer numerous advantages, such as portability, high flexibility, and efficient energy harvesting capabilities. For instance, a study conducted by the University of California, Berkeley in 2010 explored the use of electrospun polyvinylidene difluoride (PVDF) nanofibers, which exhibited piezoelectric performance when mechanically stretched and electron polarized (Figure 3a) [52]. This material demonstrated a stable electrical output when subjected to mechanical stretching, with a strain magnitude of 0.085% at 0.04 and 0.10 s. The corresponding output currents measured in the experiment were 2.74 nA and 1.16 nA, respectively. The nanogenerator exhibited remarkable flexibility and could be integrated with other micro/nano tools. This principle could serve as the foundation for powering wireless sensors or embedding nano fibers into woven fabrics to enhance the power output of portable electronic devices. In 2012, Feng-Ru Fan and colleagues at the Georgia Institute of Technology developed a flexible triboelectric generator, as illustrated in Figure 3b [53]. This TENG is constructed by stacking two polymers with different triboelectric properties, with metal films positioned on the top and bottom surfaces of the device. When subjected to external mechanical deformation, the two films rub against each other, generating equal but opposite charges on both sides. The polymer TENG can generate up to 3.3 V output voltage, with a power density of 10.4 mW/cm^3. Experimental results have demonstrated that TENGs have the potential to harvest energy from various sources, such as human activity, rotating tires, ocean waves, and mechanical vibrations.

In 2017, F. Xing from the Beijing Institute of Nanoenergy and Nanosystems designed a TENG (Figure 3c) specifically aimed at harvesting low-frequency walking energy [54]. The experiment capitalized on the human body and the ground as the friction system's electrodes, with rubber soles employed to capture mechanical energy during human motion. As the rubber layer undergoes compression by the weight of the human body and comes into contact with the ground, electron transfer occurs from the ground to the rubber layer. Consequently, a potential difference is generated between the rubber and the ground, resulting in the production of a pulse-crossing current.

In subsequent research, the triboelectric nanogenerator has transitioned from theoretical concepts to practical applications. It has been utilized for various purposes, such as harvesting human motion energy to enable signal transmission, serving as a power supply for microelectromechanical systems (MEMS), and even leveraging electrostatic effects for the isolation of the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2).



(a)Direct−write piezoelectric polymeric nanogenerator

(b) Flexible triboelectric generator

(c) Natural triboelectric nanogenerator

(d) Flexible and wearable medical devices

(e) Triboelectric nanogenerator based on human fingernail

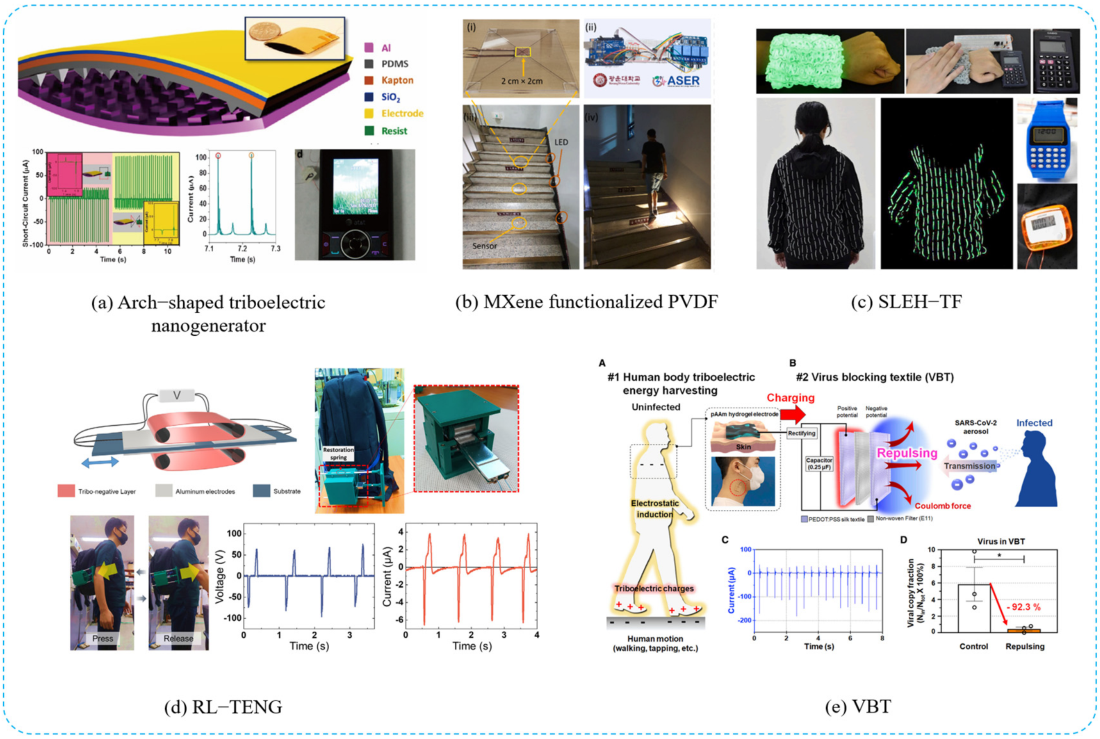
Figure 3. TENG device based on human motion (A) [52–56].

2.2.1. Transmission Signal

In 2016, Khan et al. from the University of California, Berkeley developed a wearable sensor system utilizing flexible and stretchable materials as a wearable medical device (Figure 3d) [55]. This novel device integrates low-power silicon-based electronic components with flexible wearable sensors to enable real-time monitoring and medical diagnosis of vital signs, including temperature, heart rate, respiratory frequency, blood pressure, and blood sugar levels. To collect energy from heartbeats, the device was placed on the chest, and the vibrations generated by the heartbeat were detected by the flexible sensors. This experiment demonstrates the potential of flexible wearable sensors in the field of human medical equipment. In 2018, Jiangming Fu from Ocean College, Zhejiang University conducted a study on the design of a TENG that harnesses the power generated by human nails (as shown in Figure 3e) [56]. This research demonstrated that nails can serve as efficient high-friction electro-materials, thus expanding the range of materials suitable for friction-based power generation. The experimental results revealed that when the TENG was subjected to friction with nails, it achieved a maximum open circuit voltage of 87.3 V and a maximum short-circuit current of 3.2 μA. Moreover, the TENG exhibited a remarkable maximum power density of 122 mW/m^2 at a load resistance of 23 MΩ. Subsequently, power generation gloves were employed to convert mechanical energy from hand motions into electrical energy, which was further rectified and utilized to illuminate an LED light. This study presents the feasibility of utilizing TENG devices in the field of human characteristics recognition.

2.2.2. Power Supply to Small Equipment

In 2012, Wang S. developed an arched TENG by utilizing contact electrification between a polymer thin film and a thin metal tablet (as shown in Figure 4a) [57]. The TENG comprises a Polydimethylsiloxane (PDMS) top plate and an aluminum foil bottom plate, demonstrating high energy conversion efficiency of up to 10–39% through foot pressure testing. This TENG is capable of powering light-emitting diodes (LEDs) and charging lithium-ion batteries. Additionally, it can be employed as an adjustable power module for wireless sensor systems and commercial mobile phones.



(a) Arch−shaped triboelectric nanogenerator

(b) MXene functionalized PVDF

(c) SLEH−TF

(d) RL−TENG

(e) VBT

Figure 4. TENG device based on human motion (B) [57–61].

In 2020, Trilochan Bhatta from Kwangwoon University in the Republic of Korea presented a novel electric textile design. The study involved the integration of MXene ($Ti_3C_2T_x$) into the Polyvinylidene fluoride (PVDF) substrate followed by electrospinning processing, which effectively enhanced the dielectric performance and surface charge density of the nanofibers [58]. Experimental results demonstrate that the device can quickly charge capacitors and sustain low-power electronic devices and commercial LEDs.

In 2022, Dong-Min Lee, Irfan Shabbir, and their team from Hanyang University introduced a novel rolling triboelectric nanogenerator (RL-TENG) design (as illustrated in Figure 4d) [59]. This design incorporates a metal layer and graphene nano-doped PDMS material. The inclusion of these additives enhances the TENG's dielectric constant and charge storage capacity, minimizing surface damage while achieving high electricity output. The researchers conducted experiments by utilizing the swing motion of the elbow joint during human walking to generate mechanical energy, which was then converted into electrical energy. The TENG demonstrated a remarkable high-voltage output of up to 821 V. In the same year, Lei Li from Chung Hsing University proposed a novel self-luminescing and energy harvesting triboelectric fiber (SLEH-TF) design (as depicted in Figure 4c) [60]. This design was inspired by biological glowing phosphorus and can be utilized as a source of power supply for sensors and human–machine interface power supplies in wearable devices. The fiber comprises a conducting thread covered with elastic, phosphorescent triboelectric composite material, and can be knitted into a large-area highly stretchable fabric. Through friction between fabrics, human biological energy is converted into electrical energy.

2.2.3. Isolate Virus

In 2022, Minki Kang and the research team from Sungkyunkwan University and Seoul National University developed a virus−blocking textile (VBT) design (as shown in Figure 4e) [61]. This innovative textile utilizes nanotechnology and harnesses human friction-generated electricity to apply a coulomb force to airborne particles, effectively blocking SARS-CoV-2. The VBT devices generate electrical current through human motion and continuously supply the textile with a negative potential, enabling it to repel virus with a negative charge. Experimental results demonstrate that the VBT can effectively block 99.95% of airborne SARS-CoV-2 particles.

The energy capture devices mentioned in this section are summarized in Table 1, including important information such as materials, structure, installation location, experimental equipment, and power output.

Table 1. Summary of TENGs.

Research Institutions	Devices	Material	Body Parts	Experiment Apparatus	Load	Output Effect
University of California [52]	Polyvinylidene difluoride nanofiber	Electrospinning, polyvinylidene difluoride	Whole body	Oscilloscope, Current Amp	Commercial LED	A strain of 0.085% applied over 0.04 and 0.10 s, output currents of 2.74 and 1.16 nA
Georgia Institute of Technology [53]	Triboelectric generator	Kapton film, Flexible PET substrate	Whole body	Oscilloscope, Current Amp	Load circuit	Power density of 10.4 mW/cm^3, up to 3.3 V output voltage
Chinese Acad Sci, Beijing Inst Nanoenergy & Nanosyst [54]	TENG	PVDF, rubber	Foot	Keithley system electrometer, Stanford low-noise current preamplifier	LED	Open-circuit voltage 400 V, short-circuit current 12 µA
Univ Calif Berkeley [55]	Wearable sensor system	Graphene, AgNW	Whole body	Electrometer, Oscilloscope	Load circuit, LED	The scope of harvesting energy in the heart about 0.5–4 mV and 0.05–4 µA
Ocean College, Zhejiang University [56]	TENG	Nail polish powder, Teflon glue	Finger	Fourier Transform infrared spectroscopy, STANFORD SR560, Bruker VERTEX 70	LED, recognition system	87.3 V open-circuit voltage, 3.2 µA short-circuit current, 122 mW/m^2 power density
Georgia Inst Technol [57]	Arched TENG	Polydimethylsiloxane (PDMS), aluminum foil	Human motion joints	Oscilloscope, Current Amp	wireless sensor, mobile phone	230 V open-circuit voltage, 15.5 µA/m^2 ampere density, 128 mW/cm^3 volume energy density
Kwangwoon University [58]	Nano-fiber	MXene ($Ti_3C_2T_x$) and PVDF composite	Foot, fabric	Electrometer, Force gauge, electrodynamic shaker	Low-power electronic equipment	4.6 mW output power can be provided
Hanyang University [59]	Rolling triboelectric nanogenerator	Metal layer, graphene nano-doped PDMS	back	Oscilloscope (TDS 2024C, Tektronix), Current Amp (DLPCA-200, Femto)	40 red LED	164 V open-circuit voltage, 10 µA short-circuit current

Table 1. *Cont.*

Research Institutions	Devices	Material	Body Parts	Experiment Apparatus	Load	Output Effect
Chung Hsing University [60]	Self-luminescing and energy harvesting triboelectric fiber	Elastic phosphorescent triboelectric composite	Arm, Sweater	HTC LX-103 luxmeter, Keithley 6514 SR570	Lumines-cent fiber	250 V open-circuit voltage, 80 μA short-circuit current, simultaneously emit long-lasting visible light (50 mcd m^{-2})
Sungkyunkwan University [61]	Virus-blocking textile	Conductive PEDOT, PSS fabric	Mouth	electron microscope, multimeter (Donghwa electronics, DM-1010)	VBT	259.6 μA short-circuit current, block 99.95% of SARS-CoV-2 in the air

2.3. Summary

The excellent compatibility between the TENG and the human body facilitates efficient energy harvesting from human motion. The movement of the human body induces friction between the TENG and surrounding objects, resulting in the generation of potential difference on the material's surface and subsequent electrical current output. In the current study, while most TENGs exhibit high open-circuit voltage, their output current typically remains at the microampere (μA) level, which is insufficient to power most devices. Consequently, these TENGs are commonly employed in sensing devices or health monitoring systems. The material, structure, energy conversion efficiency, and stability aspects of the TENG can be summarized as follows.

2.3.1. Material

The manufacturing of triboelectric nanogenerators typically involves the use of various materials, including metals, polymers, and carbon compounds. These materials possess favorable triboelectric properties and electrical conductivity, as well as sufficient mechanical strength and wear resistance. Additionally, factors such as cost, availability, and production processes are also taken into account when selecting materials for TENG fabrication.

2.3.2. Structure

The TENG exhibits a diverse range of structures, including single-layer, double-layer, and triple-layer configurations. A single-layer TENG primarily consists of a friction pair and a capacitor. A double-layer TENG comprises two single-layer TENGs, while a three-layer TENG incorporates three single-layer TENGs. The construction of the TENG should aim to maximize the contact and friction areas to enhance the output voltage and current. Consequently, complex structures such as multi-layer superposition, triangular designs, sawtooth patterns, and nanostructures can be employed to increase the friction area, while bending or stretching mechanisms can effectively augment the contact area. Furthermore, it is important to consider the stability and durability of the chosen structure.

2.3.3. Energy Conversion Efficiency

The energy conversion efficiency of the TENG primarily relies on the selection of materials and structure. Firstly, enhancing the energy output can be achieved by increasing the contact pressure between the two materials and modifying the friction direction to amplify the friction force. Secondly, optimizing the charge distribution can be accomplished by adjusting the charge density and electrode shape. Lastly, improving the energy conversion efficiency involves reducing the internal resistance and refining the circuit design to minimize the contact resistance between electrodes.

2.3.4. Stability

To ensure the stability of the energy output in TENG, it is crucial to select materials with excellent chemical stability, high mechanical strength, and superior wear resistance. Moreover, incorporating tensile and bending structures can enhance the stability of the overall system while reducing fatigue and potential damage. Optimal positioning of the TENG involves placing it in a dry, dust-free, and low-temperature environment, while avoiding excessive humidity, temperature fluctuations, electric field interference, and other detrimental factors.

2.4. Challenge

Human motion triboelectric nanogenerators require the use of appropriate materials that possess a high degree of sensitivity and durability. However, the current preparation technology still faces certain challenges, including high production costs, extended production cycles, and complex quality assurance processes, which require further enhancement and optimization. The energy output of TENGs tends to be low and unstable. Improving energy conversion efficiency largely depends on researching new materials and structures. Since most TENGs require direct contact with the human body and yield high output voltage, ensuring their safety is crucial. Therefore, additional experiments and studies are necessary to evaluate the potential impact of such devices on human health.

3. Study on Electromagnetic Energy Harvesting

In our daily lives, wind power, hydropower, and thermal power generation all rely on the core principle of electromagnetic induction technology [62–65]. Compared to other energy harvesting technologies, electromagnetic energy harvesting devices often have larger power output, such as backpack devices that can achieve watt-level power output, thus having advantages in terms of power output magnitude and stability.

3.1. Electromagnetic Power Generation Technology

The phenomenon of electromagnetic power generation was initially discovered by the British scientist Faraday in 1831. Its principle is based on the induction of current when a conductor, within a closed circuit, intersects magnetic lines of induction—a phenomenon referred to as magnetic induction. The electromagnetic generator operates upon this principle. Currently, electromagnetic power generation has emerged as a significant area of interest in microelectronic equipment power supply technology [66,67]. The core components of electromagnetic power generation are permanent magnets and induction coils. The working principle entails the relative motion between the permanent magnet and the induction coil, resulting in the cutting of magnetic induction lines. Consequently, the induction coil generates an induced electromotive force and a corresponding current along the wire [68].

In the closed circuit, the electromagnetic induction equation is:

$$\begin{cases} \varepsilon = n\frac{\Delta\varnothing}{\Delta t} \\ \varepsilon = -BLVsin\theta \\ E = -\frac{BL^2\omega}{2} \end{cases} \tag{2}$$

ε is the induced electromotive force, n is the number of coil turns, $\Delta\varnothing$ is the flux variation, Δt is the change time, B is the induction intensity, L is the conductor length, V is the speed of cutting magnetic induction, θ is the angle between the directions of V and B, and ω is the angular velocity.

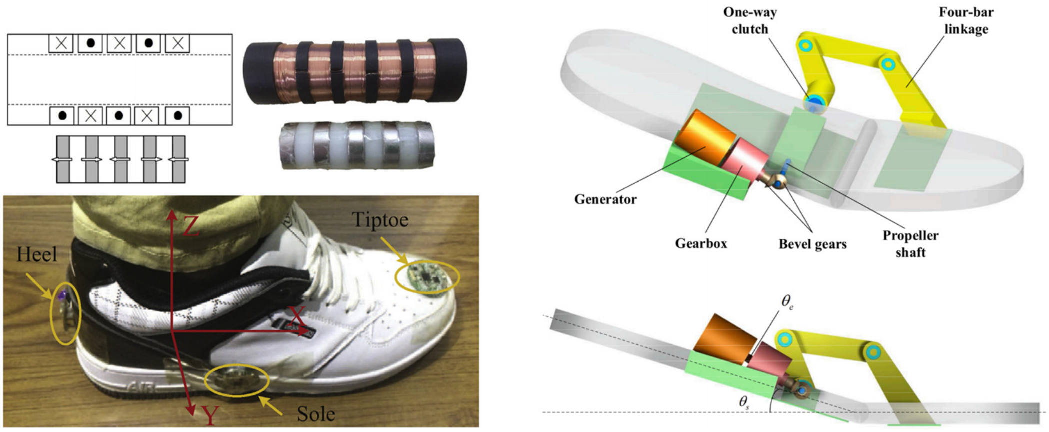
3.2. Research on Electromagnetic Harvesting Devices

Electromagnetic human energy harvesting devices primarily aim to achieve efficient energy harvesting by converting human motion into mechanical motion and subsequently utilizing a mechanism to increase the frequency of mechanical motion [69]. This paper introduces electromagnetic energy harvesting devices from various body parts, including the foot, based on their respective energy harvesting positions.

3.2.1. Electromagnetic Energy Harvesting Devices Based on Foot Movements

The foot experiences higher levels of pressure and exhibits greater motion frequencies compared to other body parts. Consequently, numerous studies consider the feet an excellent site for energy harvesting within the human body. S P Beeby and his colleagues form University of Southampton presents a small (component volume 0.1 cm^3, practical volume 0.15 cm^3) electromagnetic generator utilizing discrete components [70]. Magnet size and coil properties were optimized and 30% of the power supplied from the environment can be delivered to useful electrical power in the load. Its micro size makes it suitable as an energy harvesting device for foot motions. In 2011, P. Zengjie H. from the Illinois Institute of Technology designed a double-sided stator linear motor with a moving permanent magnet and a soft magnetic gasket [71]. Finite element analysis (FEA) was conducted on the geometric model of the design to estimate the real-time voltage of the energy harvester. The experiment further proposed a cascade boost-buck converter with appropriate control to maximize power extraction from the linear generator and charge a lithium-ion battery at a constant current. The energy harvester exhibits a power density of 8.5 mW/cm^3 at a typical foot speed. In 2016, Y. Liu, W. Fu, W. Li, et al. from Hong Kong Polytechnic University and the University of Pittsburgh designed a combined energy harvesting device consisting of a trans-rotating magnetic gear (TRMG) and a disk axial flux permanent magnet generator (AFPM) [72]. The main concept behind this design is to utilize TRMG to convert linear foot motion into rotation, thereby driving the AFPM to generate electricity.

In 2018, Peng from Beijing Institute of Technology developed a multipole linear permanent magnet generator (MLPMG) that was positioned on the heel (Figure 5a) [73]. The experimental outcomes revealed that the output power of the energy harvesting device is influenced by the gap between the motor stator and rotor, as well as the thickness of the motor gap. Additionally, a negative correlation was observed between these parameters. In 2022, Suo Wang and his colleagues from Northwestern Polytechnical University presented a novel electromagnetic energy harvester based on the bending of the sole to provide electric energy to portable sensors and small devices (Figure 6b) [74]. A four-bar linkage mechanism was employed to transform the bending motion of the sole into the rotation motion of the propeller shaft and the rotation was eventually transferred to the electromagnetic generator by the bevel gears and the gearbox. For a 72 kg test person, the presented harvester can effectively work at the walking speeds ranging from 1 km/h to 7 km/h with the average output power around 10 mW.



（a）A type of multipolar linear permanent magnet generator

（b） A novel electromagnetic energy harvester based on the bending of the sole

Figure 5. Electromagnetic energy harvesting devices based on human motion (A) [72,74].

3.2.2. Electromagnetic Energy Harvesting Devices Designed for Other Body Parts

The working principle of these devices involves utilizing joint swing and body vibration to drive a generator. The devices are primarily installed on the forearm and calf to obtain a greater centrifugal force, thereby increasing the internal vibration frequency. In 2015, a group of researchers including D.F. Berdy from the School of Electrical and Computer Engineering at Purdue University proposed an electromagnetic energy harvester that utilizes magnetic levitation for vibration energy harvesting (Figure 6a) [75]. The device incorporates a cavity design where a magnet is suspended inside, enabling the cutting of magnetic induction lines when it vibrates. In the experiment, the device is positioned on the front chest of the human body, and the average voltage and power values are compared and analyzed under different magnet counterweights, movement speeds, and load resistances. In 2016, researchers including C.R. Saha, T.O. Donnell, and Wang from the Tyndall National Institute at Cork University in Ireland proposed a human motion energy harvesting device based on the electromagnetic effect (Figure 6b) [76]. The device was mounted on a backpack during the experiment, and the human motion during walking and jogging was tested under the resonance of the vibrating mechanism. The experimental findings indicate that the device can generate power ranging from 300 µW to 2.5 mW through human motion. In the same year, a team of researchers at Kwang Woon University, including Miah A. Halim, proposed a small electromagnetic energy harvester (EMEH) that utilizes two magnetic fluxes to guide the magnetic stack and capture energy from human motions such as shaking hands, walking, and jogging (Figure 6c) [77]. The device enhances the magnetic flux density in the energy harvesting structure of a given size by directing the magnetic force line through the soft magnetic material. The small EMEH is capable of detecting low-frequency vibration caused by human motion and converting it into high-frequency vibration supported by the spring structure. In 2017, Wei Wang, Junyi Cao, et al. from Xi'an Jiaotong University presented a tunable magnetic-spring based electromagnetic energy harvester to harvest vibration energy from human motions. This harvester consisted of a hollow tube with two magnets fixed to both ends and a magnetic stack moving inside it. The best method of magnetic stack was chosen according to the generated voltage from simulation. Experimental results under harmonic excitation with different excitation level showed that the harvester has potential to generate electricity for a broadband frequency range [78].

In subsequent research, researchers have started to explore the applicability of electromagnetic energy harvesting for powering or sensing microelectronic devices. In 2021, Ning Zhou and colleagues from Xi'an Jiaotong University and University of Bath presented a Halbach array enhanced electromagnetic energy harvester with swing pendulum to maximally exploit the limb swing excitations. The structure of the harvester was composed of bearings, springs, a shaft, four magnets (NdFeB, N35) and one large coil or four small coils (Figure 6d) [79]. The magnets in the proposed device were organized in a Halbach Array to improve the energy harvesting performance under human motion. Additionally, it maximizes the utilization of limb swing for excitation. Zhongjie Li and colleagues from Shanghai University and Tongji University developed a wearable millimeter energy generator (Figure 6e) [80]. This innovative device combines two novel technologies: variable frequency piezoelectric power generation through impact effects and electromagnetic power generation with instantaneous change of magnetic flux density. By harnessing the kinetic energy generated during running, the wearable millimeter energy generator is capable of converting it into an impressive 2.1 W of instantaneous power.

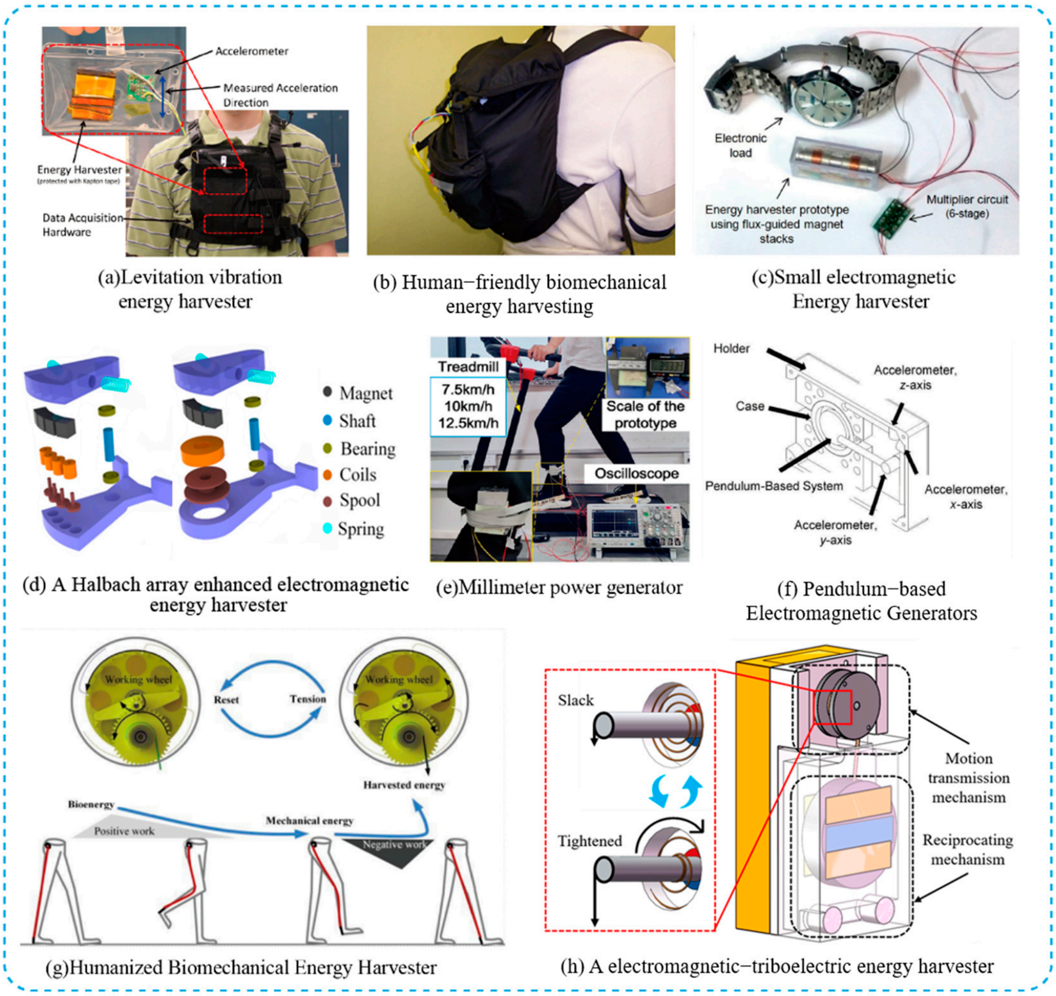


Figure 6. Electromagnetic energy harvesting devices based on human motion (B) [75–77,79–83].

In 2022, Hesam Sharghi and Onur Bilgen from Rutgers University in New Jersey investigated an energy harvesting device featuring a pendulum system that can be positioned on various joints of the human body (Figure 6f) [81]. Results indicate that as walking speed increases, the device's output power also increases. Through the use of a more precise walking trajectory, the wearable energy harvester's output voltage and power can be more accurately predicted. Hongxiang Zou, from the Hunan Institute of Engineering Key Laboratory of Automobile Power and Transmission System, proposed a biomechanical energy harvesting device enhanced with a compliant traction mechanism in the same year (Figure 6g) [82]. The device is worn around the waist and includes a traction rope that connects to the ankle. As the knee joint swings during motion, the traction rope tightens which subsequently causes the device to rotate and increase in frequency. The rotation of the device's internal magnet completes the cutting magnetic induction line motion with the external coil. In experiments, the device proved capable of supplying power to commercial intelligent electronic devices, verifying its potential for self-powered emergency calls, location and tracking, health monitoring, and physiotherapy. In 2023, Krzysztof Kecik and Ewelina Stezycka from Lublin University of Technology proposed an electromagnetic energy harvester which improves the resonant bandwidth (60–1200 rad/s) and output power (0.2 W) [83].

The energy capture devices mentioned in this section are summarized in Table 2.

Table 2. Summary of electromagnetic energy harvesting devices.

Research Institutions	Devices	Material and Structure	Body Parts	Experiment Apparatus	Load	Output Effect
Illinois Institute of Technology [71]	Double stator linear motor	Magnetized square magnet, laminated silicon steel, spiral spring	Sole of foot	Oscilloscope, voltage-current conversion amplifier	Sensing equipment	Power density: 8.5 mW/cm^3
The Hong Kong Polytechnic University [72]	Trans rotating magnetic Gear (TRMG) and Axial Flux Permanent Magnet Generator (AFPM)	Ring magnet, Teflon tube, copper wire	Foot part	ADXL321 Biaxial accelerometer and oscilloscope	External resistance	Instantaneous output power: 6.8 W
University of Southampton [70]	A micro electromagnetic generator	Four magnets, four magnets, a wound coil	Various parts of the human body	Not mentioned	External resistance	Power of 46 µW, voltage of 428 mV
Beijing Institute of Technology [73]	Multipolar linear permanent magnet generator	Magnet wafers (NdFeB) and 3D-printed spacer	foot	PC-based data acquisition test bed, Oscilloscope	External resistance	The maximum output power is 20 mW
Northwestern Polytechnical University [74]	Energy harvester based on the bending of the sole	Four-bar linkage, brushless DC electromagnetic generator	Sole of foot	Data acquisition equipment (DH8303, DONGHUA)	External resistance	Power density 0.43 mW/cm^3 (4 km/h)
Purdue University [75]	Electromagnetic magnetic levitation	Suspended magnetic net, fixed magnet, copper wire	Chest backpack	TIRA TV 51120 Electric shaking table, ADXL335 Accelerometer	External resistance	Average power 342 µW
University College Cork, Ireland [76]	Human motion energy harvesting device based on electromagnetic effect	Ring magnet, Teflon tube, copper wire	Backpack	ADXL321 Biaxial accelerometer, XR440 data recorder	External resistance	Average power 0.3–2.46 mW
Kwangwoon University [77]	Small electromagnetic energy harvester (EMEH)	Coil, compression spring, magnet	Wrist	Oscilloscope (TDS5052B), Accelerometer (MPU6500 3-axis accelerometer)	Smart phone, battery	Average power 203 µW

Table 2. *Cont.*

Research Institutions	Devices	Material and Structure	Body Parts	Experiment Apparatus	Load	Output Effect
Xi'an Jiaotong University [78]	Magnetic-spring based energy harvester	Hollow tube, N35 permanent magnets, magnetic stack	leg	Digital dynamometer, electromagnetic vibrator, oscilloscope (MSOX3052A)	External resistance	Maximum output power 10.66 mW (8 km/h)
Xi'an Jiaotong University [79]	Array enhanced electromagnetic energy harvester for pendulum	White resin 3D printing, copper coil, magnet	Calves, elbows, neck	Power amplifier (E5874A), Oscilloscope (DSOX3014A)	Watches, sensors	Average power 0.38 mW, The mass power density 23 mW/g
Shanghai University, Tongji University [80]	Wearable millimeter power generator	Piezoelectric ceramics, magnet bracket, spring, coil	Calves, wrists	Rectifier (MIC W04M), Oscilloscope	LED, lithium battery	Instantaneous power: 2.1 W
Rutgers, The State University of New Jersey [81]	Human joint energy harvesting device based on pendulum system	White resin 3D printing, copper coil, magnet	Each motion joint of the human body	Oscilloscope	External resistance	Voltage: 0.54 V, Power: 13.7 µW
Hunan Institute of Engineering [82]	Human-friendly biomechanical energy harvester	large gear, reset spring, small gear, pawls, and ratchet wheel	Waist	Not mentioned	500 LED lights	Average power of 0.22 W while walking (4 Km/h)
Lublin University of Technology [83]	Two-degrees-of-freedom electromagnetic energy harvester	Cylindrical tube, two moving magnets, a stationary coil	Not mentioned	Shaker, amplifier	External resistance	Bandwidth (60–1200 rad/s) and output power (0.2 W)

3.3. Summary

Electromagnetic human body energy harvesting devices possess simple structures and low impedance, and generate large output currents, resulting in high levels of electric energy output which can power most small equipment (e.g., handheld Global Positioning System, satellite phone, LED headlamp, smart watch). These devices can be analyzed from various perspectives, such as material, structure, energy conversion efficiency, and wearability.

3.3.1. Materials

Electromagnetic energy harvesting devices for human motion consist primarily of magnetic materials, coils, and mechanical structures. Of these, magnetic materials are critical for producing the necessary magnetic field and induction intensity required to convert mechanical energy generated during physical activity into electric energy. Devices can enhance their mechanical properties, comfort, and adaptability by selecting high-performance, low-energy-consumption, lightweight, and soft materials, such as high-strength cellulose and carbon fiber.

3.3.2. Structure

The structure of these devices typically consists of a mechanical vibration generator and an electromagnetic energy converter. The mechanical vibration generator is typically composed of a mechanical structure and vibration system, which generates mechanical vibration energy through the motion of the human body. On the other hand, the electromagnetic energy converter mainly includes coils, magnetic fields, and circuits, which convert mechanical vibration energy into electric energy. By conducting simulation analysis, dynamic testing, and other methods, the device's structure can be designed to achieve optimal energy conversion efficiency and dynamic stability while minimizing interference and impact on the human body.

3.3.3. Energy Conversion Efficiency

Due to the matching of capturing joint motion kinetic energy, the power output of the electromagnetic energy harvesting device has reached a relatively high level, but the attainable power density is still relatively low. The utilization of advanced energy conversion technologies, such as multistage energy conversion and adaptive control, can further enhance energy conversion efficiency and output power while minimizing energy loss and waste.

3.3.4. Wearability

To enhance energy harvesting efficiency, many devices require a structural design that increases frequency due to the limited range of human joint movement. However, this often results in larger device volumes. Furthermore, an improper structural design can interfere with human activities. Therefore, it is crucial for the shape, size, and wearing method of the device to adhere to ergonomic principles. Moreover, by integrating technologies like flexible electronics and wireless communication, these devices can achieve a lightweight, flexible, and comfortable user experience, ultimately enhancing human–machine interaction and operational convenience.

3.4. Challenge

The efficiency of converting mechanical energy into electrical energy is crucial for human motion electromagnetic harvesting devices. These devices only capture and store small amounts of energy in the negative work stage, and higher efficiency means less metabolic costs under the same power output, thereby reducing the impact on the wearer's own movement. While current generator and rectifier technologies have limitations, it is imperative to further enhance the generation efficiency and minimize energy loss. These devices find applications primarily in high-frequency motion scenarios such as walking or running. However, maintenance costs can be high due to the frequent replacement of battery components during motion. The internal structure of electromagnetic energy harvesting devices is relatively complex, often resulting in large volumes and heavy masses. Therefore, optimizing the device's structure and materials is necessary to improve its compatibility with the human body.

4. Study on Piezoelectric Energy Harvesting

The piezoelectric effect in α quartz crystal was discovered by Jacques and Pierre Curie in 1880, marking the beginning of the history of piezoelectricity. During World War I, Paul Langevin utilized the voltage effect of α quartz crystals to create an underwater ultrasound detector [84]. In 1946, the Massachusetts Institute of Technology applied a DC high-voltage electric field to barium titanate ferroelectric ceramics, leading to the study of the first piezoelectric ceramic [85,86]. Subsequent research focused on utilizing piezoelectric materials for applications such as pressure transducers, high-frequency transducers, wave filters, and resonators [87–90]. Since the turn of the century, piezoelectric materials have also been crucial components in ultrasonic motors, gyroscopes, aerospace technology, medical equipment, and optical instruments [91–93]. The advancement of integrated materials, low-energy electronic components, and piezoelectric materials has led to the maturation of piezoelectric vibration energy harvesting technology [94–96].

4.1. Piezoelectric Power Generation Technology

The piezoelectric effect refers to the deformation of piezoelectric materials under the action of external force, through coupling material dielectric properties and elasticity, in the material surface to form opposite charges to produce a polarization phenomenon [97,98].

4.1.1. Theory and Model of Piezoelectric Effect

Figure 7 illustrates the positive piezoelectric effect, which is a polarization phenomenon resulting from deformation. Conversely, when an electric field is applied to piezoelectric materials, the material undergoes polarization and experiences a deformation process known as the inverse piezoelectric effect [99]. There are two standard modes of the piezoelectric effect: d_{31} (Longitudinal) and d_{33} (Transverse) (as depicted in Figure 8) [100,101]. When an external force acts on the piezoelectric materials, equal and opposite charges are generated on the top and bottom surfaces. In the d_{33} model, the direction of mobile charge is parallel to the direction of the external force. On the other hand, in the d_{31} model, the charge moves perpendicular to the direction of the external force.

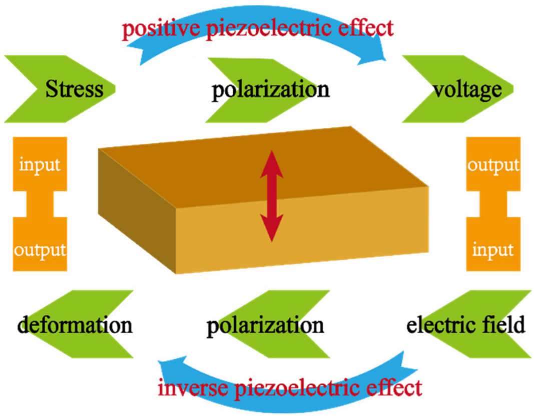


Figure 7. Schematic diagram of positive and inverse piezoelectric effect [99].

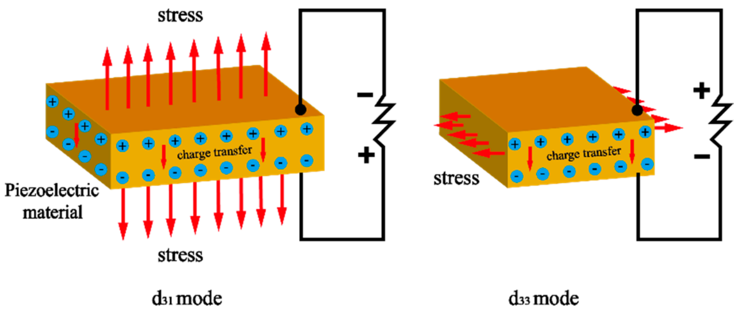


Figure 8. Schematic diagram of d_{31} and d_{33} mode [100].

There is a linear relationship between the charge density generated by the positive piezoelectric effect and the contact stress when external forces commonly put stress on the piezoelectric materials. That is,

$$\vec{\delta} = d \cdot \vec{T} \tag{3}$$

Among them, $\vec{\delta}$ is charge density (C·m^{-2}), d is piezoelectric constant strain (N/Vm), and $\vec{T}$ is stress of piezoelectric material (N·m^{-2}).

When an electric field is applied to both ends of piezoelectric materials, it results in the occurrence of positive and negative charges within the material, causing internal relative displacement and polarization. This polarization, in turn, leads to the corresponding mechanical deformation. The piezoelectric effect that arises from the applied electric field is referred to as the inverse piezoelectric effect. In general, there is a linear relationship between the applied electric field and the resulting mechanical deformation. That is,

$$\vec{x} = d \cdot \vec{E} \tag{4}$$

Among them, $\vec{x}$ is mechanical strain caused by piezoelectric effect and $\vec{E}$ is applied electric field strength ($V \cdot m^{-1}$).

4.1.2. Piezoelectric Materials Research

The foundation of piezoelectric vibration energy harvesting lies in piezoelectric materials. Key performance parameters include the piezoelectric constant, electromechanical coupling coefficient, dielectric constant, and Curie temperature [52]. These materials can be categorized into inorganic and organic piezoelectric materials. Inorganic piezoelectric materials consist of piezoelectric crystals (single crystals) and piezoelectric ceramics (polycrystalline) [98,101,102]. Commonly used piezoelectric ceramics include $Pb(Zr_1 - xTiO_3)$ (PZT), $BaTiO_3$ (BT), $PbNb_2O_6$, etc. [103–106]. Piezoelectric ceramics exhibit high piezoelectric constant, strain, dielectric constant, and plasticity. However, they are associated with significant electrical loss and poor stability, which makes them less suitable for high-frequency energy harvesting applications.

Organic piezoelectrics, specifically piezoelectric polymers such as polyvinylidene fluoride (PVDF), as well as piezoelectric composite materials [52,102,107], exhibit favorable characteristics including low density, low impedance, high voltage constant, and good flexibility. These properties make them well suited for applications such as pressure sensors and ultrasonic detection [108]. However, they do have limitations, such as a lower piezoelectric constant strain and limited energy transformation capabilities.

4.2. Research on Piezoelectric Energy Harvesting Devices

The performance of piezoelectric vibration energy harvesting primarily depends on the piezoelectric material, including factors such as the efficiency of piezoelectric energy collection. This efficiency is mainly influenced by the size of the piezoelectric material, vibration frequency, amplitude, and input mode [98,109,110].

Piezoelectric energy harvesting devices can be categorized into two types based on the type of piezoelectric material used for energy harvesting: those with piezoelectric ceramics as energy harvest materials and those with piezoelectric thin films as energy harvest materials.

4.2.1. Piezoelectric Ceramic Energy Harvesting Devices

Piezoelectric ceramic energy harvesting devices are primarily designed with a cantilever structure. This structural configuration allows for increased deformation of the piezoelectric ceramics, resulting in higher energy generation. Simultaneously, this design minimizes the loss of the piezoelectric element.

In 2010, on the basis of the original rectangular double piezoelectric sheet, the performance of the trapezoidal structure was mainly analyzed by Moro L. from the University of Udine (Figure 9a) [111]. This research results showed that the installation of PZT-5A (trapezoidal structure) on the soles, subjected to sine wave acceleration excitation, resulted in a relative increase in harvested power of approximately 25–30% compared to the rectangular structure. In 2011, Haghbin N. proposed a novel design for embedded PZT power harvesting shoes at Ryerson University [112]. The device is constructed using aluminum and hard plastic to form fixed cavities within which the PZT material is embedded. When foot pressure is exerted, air is squeezed into the fixed cavity, resulting in deformation of the PZT sheet and subsequent generation of electric current. This design solves the conventional issues of poor stability and short lifespan. In the same year, Michele Pozzi from Cranfield University proposed a novel wearable energy harvesting device based on a knee joint piezoelectric mechanism [113]. By utilizing periodic knee joint rotation, this device drives the toggling of piezoelectric patches and subjects them to the appropriate excitation frequency. The power generation effect of this vibration mode of twin piezoelectric patches was simulated using the finite element analysis method. The experimental findings indicated that as the load resistance value increased from 100 kΩ to 1 MΩ, the peak of the power output started to attenuate. In 2015, Sung Joo Hwang from Hanyang University conducted research on a foot energy harvesting device (Figure 9b) [114]. The device was designed to incorporate a spring and ceramic tile, which served as an indirect means of transmitting energy in order to mitigate the impact of foot pressure and the ascending vibration frequency. This design made ceramic tile's mechanical resonance frequency matches the piezoelectric module's mechanical resonance frequency.

In subsequent studies, further analysis of the structural variations was conducted by researchers. In 2018, M.H. Ansari from the University at Buffalo designed a controlled bending structure for carrying piezoelectric bimorph sheets PZT-5A [115]. The PZT-5A sheets were attached to both sides of a curved spring steel. The spring steel was positioned vertically on the ground, and a vertical force of 2450 N was applied at the end of the spring steel. Under a load resistance of 10 kΩ and with a 0.02 mm displacement of the spring steel end, the structure was able to generate 42.3 mW of power. This innovative structure has the potential to be placed on roads or incorporated into footwear for energy harvesting applications.

In 2019, Iman Izadgoshasba from Southern Cross University conducted a study exploring the utilization of piezoelectric energy harvesting devices (PEH) to extract energy from various human body movements (Figure 9c) [116]. The experimental investigation focused on three different PEH structures: the traditional cantilever beam (PEHCB), the simple pendulum cantilever beam (PEHSP), and the double pendulum cantilever beam (PEHDP). The objective was to improve the efficiency by adopting a double pendulum system coupled with magnetic force interactions.

In 2017, researchers from Xidian University developed a piezoelectric energy harvesting device (Figure 9d) [117]. The device comprises a piezoelectric cantilever beam, transverse beam, and a cantilever beam with ferromagnetic coupling. A sleeve is employed to guide the motion of an iron magnet ball. As the calf swings, the ball strikes the piezoelectric beam, inducing vibrations. The proposed PEH can harvest the exercise incentives of the feet in different directions and stack them in a gait cycle to produce multiple output voltage peaks. In the same year, Wei Wang from Xi'an Jiaotong University developed a nonlinear piezoelectric energy harvesting device for body motion (Figure 9e) [118]. The study aimed to investigate the energy harvesting efficiency of human nonlinear sports activities in detail. The research concluded that at exercise speeds ranging from 6 to 8 km/h and with a load resistance of approximately 2 MΩ, the device exhibited multiple peak output voltages. In 2018, Halim from the University of Utah developed a limb-driven piezoelectric energy harvesting device (Figure 9f) [119]. The device incorporates a mechanical metal ball to convert low-frequency human body vibrations into high-frequency vibrations. When activated by human limbs, the sequential impacts of the ball against the flexible side wall enable the transfer of impact forces to the load mass of the piezoelectric beam. In 2019, Feng Qian from the South China University of Technology developed a device that incorporates an amplifier mechanism and twin piezoelectric patches (Figure 9g) [120]. The device's structure comprises a V-shaped slider, two right H-shaped sliders, and two combed fixtures. The H-shaped slider is responsible for bearing foot pressure and distributing the force to the two horizontal H-shaped sliders. Ultimately, the horizontal force is transmitted to the combed clamp, resulting in uniform deformation of the piezoelectric patches.

In 2020, Muhammad Iqbal from University Brunei Darussalam developed a piezo-electromagnetic hybrid generator for sustainable wearable microelectronics (PEM-IEH) to recycle wasted bionic energy during daily walking processes (Figure 9h) [121]. The device comprises two pieces of piezoelectric ceramics, magnets, and coils. The researchers integrated the device into the sole of a commercial shoe, enabling it to charge 100 μF capacitors in approximately 10 min of jogging, reaching up to 2.4 V. In 2021, Gljuscic from the University of Rijeka optimized the structure of a cantilever beam to enhance the collection of human motion energy (Figure 9i) [122]. The experiment involved installing twin piezoelectric patches onto a watch-type prototype and using an internally rotating flywheel to drive the piezoelectric vibration. By implementing a frequency upraising structure, the low-frequency vibrations (1–3 Hz) generated by human body motion were increased to vibrations with inherent frequencies of approximately 325–930 Hz. Compared to the traditional rectangular cantilever beam structure, the optimized structure demonstrated a significant increase in power output, up to 5.5 times higher.

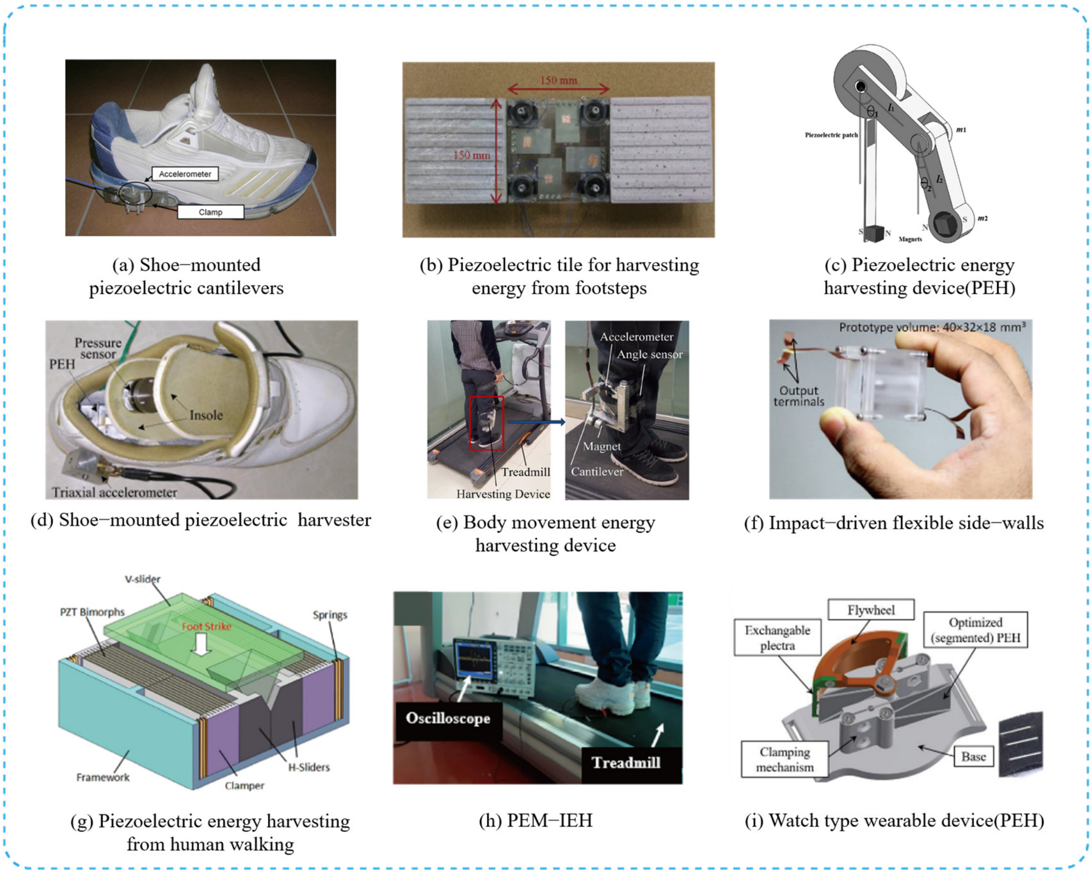


Figure 9. Piezoelectric ceramic energy harvesting devices based on the human body [111,114,116–122].

In general, the output power of piezoelectric energy harvesting devices falls between that of TENG and electromagnetic energy harvesting devices. However, the output efficiency of piezoelectric ceramic materials is influenced by their vibration frequency. Therefore, it becomes essential to enhance the devices' frequency by optimizing their structural design in order to achieve resonance at their natural frequency and attain higher energy output. It should be noted that due to the brittle nature of piezoelectric materials, they are susceptible to fatigue and have a relatively shorter service life when subjected to high-frequency vibrations.

4.2.2. Piezoelectric Film Energy Harvesting Devices

Piezoelectric films, known for their good ductility, are primarily utilized in wearable fabrics, where they undergo deformation during movements of the body's joints. In 2005, a study conducted by Barcelona Tech compared the performance of isomorphic rectangular cantilever beams with heterogeneous triangular cantilever beams using PVDF (Figure 10a) [123]. The findings revealed that the triangular-shaped cantilever beam exhibited higher efficiency compared to its rectangular counterpart. In 2009, Ding H. at Louisiana Tech University implemented a 120-layer honeycomb structure on the sole vacuum cavity to harvest the energy generated by the heel during walking [124]. This structure possesses several desirable features, including compact size, flexibility, shock absorption, lightweight design, durability, and cost-effectiveness. Consequently, this device finds applications in various fields such as pedometers, inertial navigation devices, and self-powered emergency systems. In 2014, Li XH at Georgia Institute of Technology conducted a study introducing a fiber-based hybrid nanogenerator (FBHNG), which integrates a triboelectric nanogenerator (TENG) and a piezoelectric nanogenerator (PENG), to effectively harvest mechanical energy from the surrounding environment (Figure 10b) [125]. The FBHNG is designed to capture energy from all directions in space, with the TENG positioned at the center of the device and the PENG covering the outer shell. This innovative FBHNG can be seamlessly woven into fabrics, allowing for energy harvesting from human motion while also functioning as an adaptive sensor.

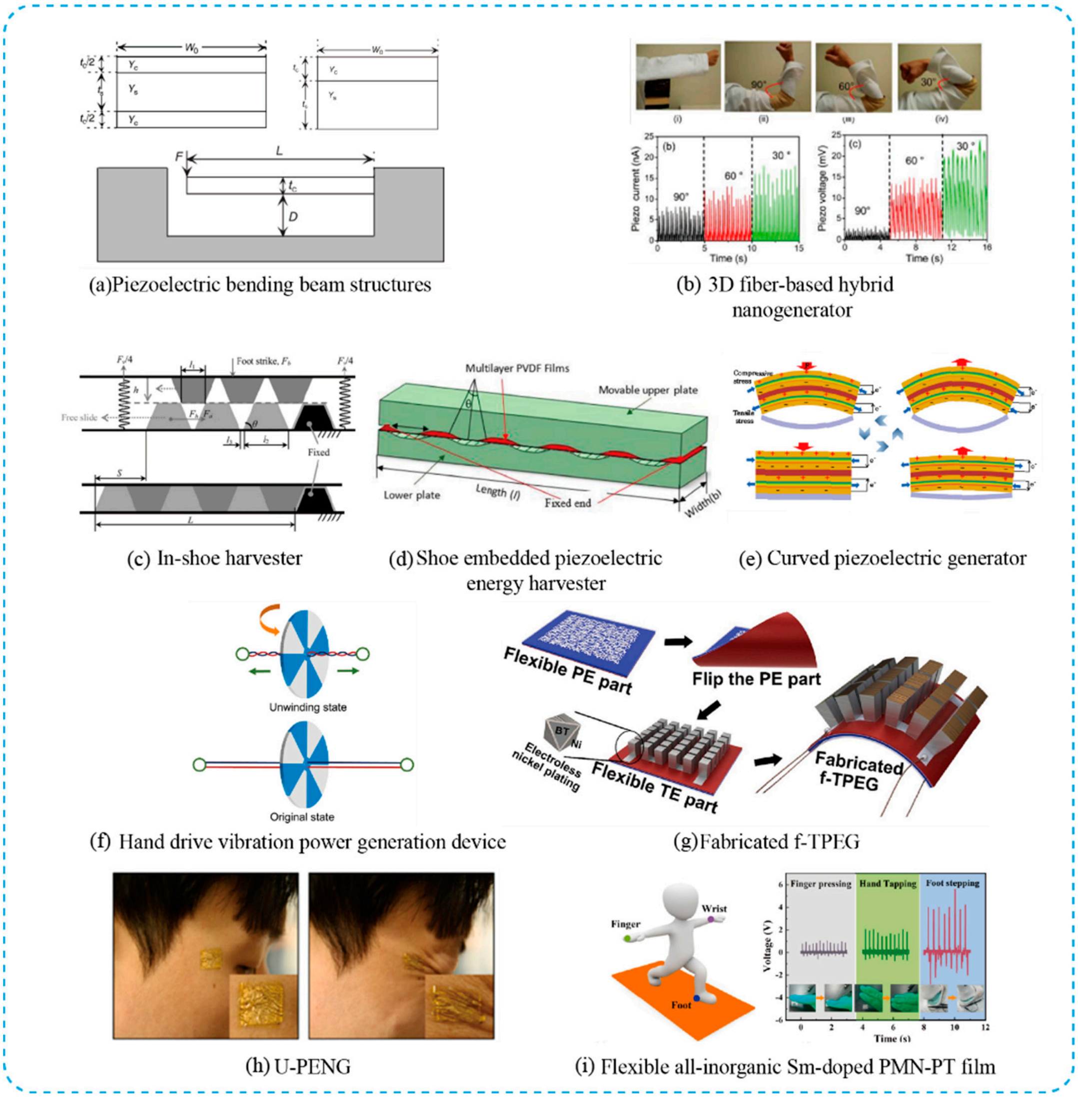


Figure 10. Piezoelectric thin film energy harvesting devices based on the human body [123,125–132].

In 2015, Mingjing Cai designed a foot energy harvesting device featuring a unique trapezoidal slider mechanism (Figure 10c) [126]. This mechanism efficiently captures the energy generated by foot impact, which is then transmitted through gears to drive micro-generators for electricity generation. In the same year, P. Saha from Jadavpur University developed two types of foot sole energy collectors utilizing PVDF material (Figure 10d) [127]. These energy collectors can be conveniently embedded within shoes, generating electricity while walking. One design features a sandwich structure, while the other adopts an elliptical structure. Woo-Suk Jung from Korea Institute of Science and Technology developed a flexible energy harvesting device that utilizes two bending piezoelectric patches for connectivity (Figure 10e) [128]. The device consists of a polyimide matrix with a thickness of 0.2 mm and a PVDF layer with a thickness of 0.1 mm. When placed on the insole and subjected to a walking frequency of 0.5 Hz by a person weighing 68 kg, the device generates an average voltage of 25 V and current of 20 μA.

In 2021, Yongjiu Zou from the University of California proposed a portable hand drive vibration power generation device that is low in cost and highly efficient. This device harnesses energy from low-frequency linear human motion (Figure 10f) [129]. By utilizing the stretching motion of the hand, the device can achieve a rotating speed exceeding 10,000 RPM. Experimental results have demonstrated that this device can power smart bracelets for health monitoring as well as portable MPEG-1 audio layer III devices for music playback. In 2021, Seoha Kim from Kyungpook National University developed an f-TPEG (flexible and Thermal-Piezoelectric Energy Generator) comprising a piezoelectric (PE) thin film made of poly (vinylidene fluoride-co-trifluoroethylene) and thermoelectric (TE) alloy blocks based on bismuth telluride (Figure 10g) [130]. In that experiment, the device successfully converted the energy generated by human finger motion into an output voltage of approximately 8 V, accompanied by a current pulse of 6 μA. In 2022, Jihoon Bae from Daegu Gyeongbuk Institute of Science & Technology designed an ultrathin piezoelectric energy nano-generator (U-PENG) utilizing poly (vinylidene fluoride-trifluoroethylene) as the base material (Figure 10h) [131]. The thickness of the U-PENG is 4 μm, allowing it to be easily attached to human skin. In a blinking experiment conducted on the human body, the device generated a voltage of approximately 120 mV and a current of 9.3 nA. The U-PENG can be seamlessly integrated with biological equipment to serve as a power supply. In the same year, Panpan Lv from the University of Jinan proposed a novel inorganic piezoelectric thin film, Sm-doped Pb(Mg1/3Nb2/3)O_3-$PbTiO_3$ (Sm:PMN-PT), as shown in Figure 10i [132]. The device exhibits excellent heat and water resistance, making it suitable for practical applications. It can be comfortably worn on the human hand and effectively power sensing systems through hand activity.

Piezoelectric films exhibit material properties similar to those of friction nano-materials, offering excellent ductility and high adaptability to the human body without being easily damaged. As a result, they are commonly embedded in clothing, fabrics, and shoe soles. However, due to their relatively low strain coefficient and dielectric constant, piezoelectric films tend to have limited energy output, primarily serving as signal transmission components.

Some of the energy harvesting devices mentioned in this section are summarized in Table 3.

Table 3. Summary of piezoelectric energy harvesting devices.

Research Institutions	Devices	Material	Body Parts	Experiment Apparatus	Load	Output Effect
University of Udine [111]	Twin piezoelectric patches of trapezoidal structure	PZT-5A, Stainless steel	Foot	Oscilloscope	Load Resistance	Harvest power increased by about 25–30%
Cranfield University [113]	Knee joint piezoelectric wearable energy harvesting device	T215-H4-303X PZT, Metal sheets	Knee joint	Laser Doppler Vibrometer (Polyetc CLV-2534)	Load Resistance	1.0 mW average power

Table 3. *Cont.*

Research Institutions	Devices	Material	Body Parts	Experiment Apparatus	Load	Output Effect
Hanyang University [114]	Foot energy harvesting device	PZT-PZNM	Foot	Oscilloscope, Current Amp	60 LED lights (WLST6030CWY)	55 mW instantaneous power
University at Buffalo [115]	A controlled bending structure to carry piezoelectric bimorph sheets	PZT-5A, Spring steel	Road, sole of shoe	Oscilloscope, Current Amp	Load Resistance	42.3 mW instantaneous power
Southern Cross University [116]	Piezoelectric energy harvesting device (PEH)	Metal cantilever beam, PZT	Lower leg, wrist	Oscillating Screen(APS-113), Accelerometer (Dytran 3305A2)	Load Resistance	The power peak is 80 µW
Xi'an Jiaotong University [118]	Nonlinear piezoelectric body motion energy harvesting device	PZT-51, magnet	Lower leg	Accelerometer (CXL04GP3), Angular Transducer (BWD-VG100), Oscilloscope	Load Resistance	77 µW average power
University of Utah [119]	Limb-driven piezoelectric energy harvesting device	PZT-5H, Silicon Resin, iron	joints	Triaxial accelerometer, data logger, Oscilloscope (TDS 5052B)	Load Resistance	The average power generated in series is 175 µW
University Brunei Darussalam [121]	Piezo-electromagnetic hybrid generator for sustainable wearable micro-electronics (PEM-IEH)	PZT, Disc magnet, Polytetrafluoroetylene, Spiral Spring	Foot	Power amplifier(Model RM–AT2900), Accelerometer (EVAL-ADXL335Z), Oscilloscope (Model GOS 6112),	Load Resistance Capacitor	Charge 100 µF capacitors within about 10 min of jogging (up to 2.4 V voltage)
University of Rijeka [122]	Watch-type wearable device (PEH)	PZT-5H	Wrist joints	Oscilloscope (DSO-X 2012A), 500 V Laser Vibrometer	Load Resistance	The power output is greater than 130 mW, and the average power output is greater than 3 mw
Georgia Institute of Technology [125]	Fiber-based hybrid nanogenerator (FBHNG)	ZnO-NRs thin film, Ti thin film, PDMS	Elbow Joint	Oscilloscope, Current Amp	Commercial capacitor, LED	Instantaneous output power density: 42.6 and 10.2 mW/m^2
Korea Institute of Science and Technology [128]	Flexible energy harvesting device	Polyimide, PVDF	Foot	Oscilloscope (DSOX3014A)	Diode chip, LED	Average voltage and current of 25 V and 20 µA respectively

Table 3. *Cont.*

Research Institutions	Devices	Material	Body Parts	Experiment Apparatus	Load	Output Effect
University of California [129]	Hand drive vibration power generation device	Fluorinated ethylene propylene(FEP), Al, electrode, Acrylic substrate	Hand	Keithley 6514 System, Current Amp (Stanford Research System SR570)	Calculator, MP3, smart wristband	Charge 220 μF commercial capacitors, up to 3 V
Kyungpook National University [130]	f-TPEG	Piezoelectric (PE) poly(vinylidene fluoride-co-trifluoroethylene) thin film, thermoelectric (TE)	Finger	Oscilloscope, Current Amp, thermometer	Load Resistance	8 V output voltage and the current pulse of 6 μA
Daegu Gyeongbuk Institute of Science &Technology [131]	Ultrathin piezoelectric energy nano-generator (U-PENG)	PVDF, TrFE	Corners of eyes, neck	Semiconductor Characterization System(Keithley 4200-SCS), Oscilloscope	Load Resistance	The voltage and current are about 120 mV and 9.3 nA
University of Jinan [132]	Inorganic piezoelectric thin film	Sm-doped Pb(Mg1/3Nb2/3) O_3PbTiO_3 (Sm:PMN-PT)	Motion joints	Oscilloscope, Current Amp	Sensor, mobile screen	Output voltage of about 6 V, a current density of 150 μA cm^{-2}, and a voltage sensitivity of about 5.86 V N^{-1}

4.3. Summary

The utilization of the piezoelectric effect in energy harvesting devices enables the conversion of mechanical energy into electric energy. In this regard, several key aspects, including material properties, structural design, energy conversion efficiency, and stability, can be summarized as follows.

4.3.1. Materials

Piezoelectric energy harvesting devices primarily comprise piezoelectric electrodes and supporting materials. Among these, the key component is the piezoelectric material, which can be either inorganic (e.g., Pb (Zr, Ti) O_3, $BaTiO_3$, etc.) or organic (e.g., polyvinylidene fluoride, polyvinyl nitrile, etc.) in nature. The piezoelectric properties of these materials can be improved through the addition of dopants and optimization of the material preparation processes.

4.3.2. Structure

Piezoelectric energy harvesting devices mainly employ various structures such as cantilever beams with added mass, coupled cantilever beams and iron balls, stacked structures, controllable bending structures, and flywheel ratchets. The choice of structure significantly impacts the energy conversion efficiency and stability of piezoelectric energy harvesting devices. To enhance performance, optimization of structure design and electrode layout is crucial. For instance, incorporating a multi-layer thin film stacking structure can increase the electrode surface area and improve energy conversion efficiency. Additionally, the use of flexible substrate materials can enhance stability and reliability.

4.3.3. Energy Conversion Efficiency

The energy conversion efficiency of piezoelectric energy harvesting devices is predominantly determined by the selection of materials and structures. To enhance the output voltage, a multi-layer thin film stacking structure can be utilized. Moreover, optimizing the electrode layout is crucial to increase the electrode surface area, mechanical stress, and vibration frequency, thereby improving the energy conversion efficiency.

4.3.4. Stability

The stability of piezoelectric energy harvesting devices is crucial for their long-term operation. It can be enhanced through the selection of highly stable materials, optimization of structure design, and electrode layout. For instance, the use of flexible substrate materials enables adaptation to diverse environments and strains, while employing materials with high stability mitigates the risk of device failure.

4.4. Challenge

Piezoelectric ceramics and films are commonly utilized as piezoelectric materials. However, long-term use of these materials can result in performance degradation or failure due to factors like mechanical stress, fatigue, and aging. Therefore, it is imperative to develop more stable and durable piezoelectric materials. Additionally, the influence of external factors such as temperature and humidity on device performance must be considered. Appropriate measures should be employed to mitigate these effects and enhance energy harvesting efficiency. Given that energy harvested by these devices is often intermittent, continuous output requires energy storage. Nevertheless, current energy storage technologies like supercapacitors and lithium-ion batteries still require improvement in terms of volume, weight, capacity, and lifespan.

5. Summary of Energy Harvesting Methods

Frictional energy harvesting is a technique that uses friction to generate tiny amounts of electricity. The technology uses the frictional effects of nanostructured materials to convert mechanical energy into electricity. There are some advantages such as small size, light weight, and high sensitivity in this technology. It can be applied to micromechanical systems, sensors, and wireless transmission equipment. However, the output current of friction nano power generation is low and the voltage is unstable, so the current and voltage need to be amplified and adjusted. Its stability and life also need to be further improved.

Electromagnetic energy harvesting is a technique that harnesses the conversion of mechanical energy into electricity through the principle of electromagnetic induction. This technology utilizes changes in magnetic fields to generate small amounts of electric energy. It offers several advantages, including high output voltage, current, and reliable performance. Applications of electromagnetic energy harvesting include wireless transmission equipment, intelligent sensors, and medical devices. However, it is worth noting that electromagnetic power generation necessitates magnetic field variations in solid structures. Therefore, it imposes higher vibration requirements, as well as considerations regarding size and weight.

Piezoelectric energy harvesting is a technique that utilizes the piezoelectric effect to generate micro electrical energy. This technology capitalizes on the mechanical deformation of piezoelectric materials to alter charge distribution, thereby generating electrical energy. The advantages of this technology encompass high output voltage and current, broad response range to vibration frequency, and compact size, making it applicable to micromechanical systems, sensors, and medical equipment. Nevertheless, it should be noted that the output voltage and current of piezoelectric energy generation are contingent upon external mechanical vibrations.

Among the examined approaches, electromagnetic actuation can offer relatively high currents at low voltages, whereas piezoelectricity can give low currents at high voltages [133]. A comparison of different ways of energy harvesting is shown in Table 4.

Table 4. Comparison of different ways of energy harvesting.

Energy Harvesting Mode	Energy Harvesting Principle	Energy Harvesting Material	Advantages	Disadvantages
Friction type	Friction generation electricity	Kapton film, AgNW electrode, nail powder, tin disulfide nanosheets (SnS2-NSs), polydimethylsiloxane (PDMS) and conductive PEDOT.	High malleability, light weight, small size, embedded design, and high adaptability to human body	High impedance, output current in the μA, cannot be used to power most devices
Electro-magnetic type	Electro-magnetic induction	Magnetized square magnet, ring magnet, copper wire, suspended magnetic net.	Simple structure, low impedance, and large output current, and can supply power for most small equipment	Large mass, large volume, mostly rigid materials, low wearing comfort
Piezoelectric type	Piezoelectric effect	PZT-5A, T215-H4-303X Piezoelectric chip, PZT-PZNM, PVDF, ZnO-NRs film, Fluorinated ethylene propylene film, PMN-PT	Piezoelectric ceramic: simple structure, light weight, high output voltage; piezoelectric film: high ductility, higher fitness with human body and not easy to damage	Piezoelectric ceramic: easy to fatigue and damage; piezoelectric film: Low piezoelectric strain coefficient, low dielectric constant, low energy output

6. Analysis of Key Technologies

Exploring the harvesting and application of human biomechanical energy, which presents a clean alternative to electrical power supplied by batteries for portable electronic devices and for computerized and motorized prosthetics [134], has emerged as a promising approach. The design and research of such devices necessitate considerations for energy harvesting mode and type, energy harvesting efficiency, miniaturization, and experimental validation. Therefore, building upon the existing design and research of energy harvesting devices, this article summarizes the following essential technologies.

6.1. Integration of Biomechanics and Energy Harvesting Technology

The integration of human motion biomechanics and energy harvesting technology holds great potential for advancing our understanding and practical applications of human motion. Specifically, human motion energy harvesting technology encompasses various technical approaches to measure and analyze the diverse forms of energy generated by the human body during movement. By leveraging this technology, we can enhance motion efficiency, optimize movement patterns, and so on.

To begin with, the exploration of human motion biomechanics serves as a fundamental basis for research in human motion energy harvesting technology. Through an investigation into the biomechanics of human motion, we gain insights into the kinematics, dynamics, and control characteristics of the human body during movement. Additionally, we can obtain precise measurements and data analysis of kinematic and dynamic parameters at each joint of the human body, thereby establishing a dependable foundation of experimental data and theoretical principles for the advancement of human motion energy harvesting technology. Moreover, human motion biomechanics research enables quantitative analysis of the generation and consumption of energy during human motion by simulating various movements. By doing so, it provides crucial technical support for the development of diverse human motion energy harvesting devices.

6.2. Adaptability of Energy Harvesting Modes and Equipment Types to Human Motions

The energy produced in human motions is mainly concentrated in the swing of limbs, such as fingers, wrists, elbows, hip joints, knee joints, and feet. In addition, the energy generated by beating, breathing, and even blinking of the heart can also be effectively harvested. Incorporating energy harvesting devices into various elements like gloves, clothing fabrics, backpacks, and shoe soles offers a convenient means of utilization for individuals. Currently, the primary modes of energy harvesting include friction, electromagnetic, and piezoelectric techniques. Electromagnetic technology possesses characteristics of high energy density and stable output. On the other hand, friction and piezoelectric methods enhance the quality of comfort, such as flexibility and lightweight design. Different parts of the human body generate energy that requires specific harvesting methods. For high-energy areas characterized by large displacements, angles, or pressures, such as knee joint rotations, lower leg swings, and foot movements, their motion frequencies are relatively regular. This allows for stable energy harvesting through electromagnetic or piezoelectric ceramic vibration. In contrast, low-energy components with small displacements and angles, such as finger joints and wrist movements, exhibit irregular motion patterns and are spatially constrained. Therefore, friction is commonly utilized to extract energy through the combination of friction nano-materials and fabrics. Additionally, for movements like respiration and heartbeats, piezoelectric films can be employed for signal transmission, such as physiological monitoring and medical sensing. Consequently, conducting research on complex energy harvesting devices that leverage the advantages of different modes is of significant importance.

6.3. Improvement of Energy Harvesting Efficiency

The energy harvesting efficiency of devices plays a crucial role in determining their output performance. However, electromagnetic, piezoelectric, and friction materials have inherent requirements for high-frequency vibration excitation. In contrast, the oscillations and limb vibrations typically encountered in human motion are predominantly low-frequency vibrations which fall short of meeting the excitation frequency criteria for energy harvesting devices. Therefore, it is necessary to enhance the frequency response through improvements in device structure design. Currently, various structural forms such as planetary wheels, ratchet wheels, magnetic coupling, cantilever beam-mass blocks, multi-source input, and others are frequently employed to enhance harvesting efficiency. These design modifications aim to bridge the gap between the low-frequency nature of human motion and the preferred frequency response of energy harvesting devices.

The electromagnetic energy harvesting devices can transform the low-frequency and large-angle swing of the limb into high-frequency rotation through a planetary wheel and ratchet system, thus providing high-frequency excitation for the motor. For the piezoelectric type, the cantilever mass and magnetic coupling can effectively increase the deformation and vibration frequency of the piezoelectric chip. The friction type has a higher impedance and often has a lower output current. The electric energy output is improved using its contact form (wavy), fixed mode (arch), and so on.

6.4. Miniaturization of Energy Harvesting Devices

The installation of energy harvesting devices primarily focuses on various joints of the human body or their integration into clothing, as they mainly aim to capture energy from human motion. This requirement imposes strict constraints on the micro-miniaturization design of such devices. Existing studies have identified that electromagnetic energy harvesting devices encounter challenges in achieving small volumes due to the necessity of coil winding and rotor–stator design. Consequently, the development of electromagnetic devices in the wearable field is limited. On the other hand, triboelectric nanogenerators (TENGs) exhibit favorable characteristics such as small size and high flexibility, making them suitable for placement in confined spaces. TENGs can harness the friction between clothing or between clothing and the human body to drive the devices. Additionally, organic piezoelectric materials used in piezoelectric energy harvesting devices share similarities with friction nano-materials, possessing high ductility. Unlike organic piezoelectric materials, inorganic piezoelectric materials primarily rely on structural design to enhance their vibration frequency, thereby improving energy harvesting efficiency. The size of the energy harvesting unit is determined by the volume of the devices, which directly impacts the magnitude of energy harvesting. The miniaturization design of these devices faces the challenge of achieving higher efficiency within limited space. Consequently, in current device designs, efforts are made to minimize structural complexity while increasing the number of energy harvesting units to enhance the volumetric energy density of the devices.

6.5. Evaluation of Energy Harvesting Experiment

An electromagnetic energy harvesting device's voltage changes are relatively stable, generally through the external load; the voltage and current amplifier are used to measure the voltage or current at both ends of the load and then through to calculate its output power [76,77,79–81].

There exist various methods for evaluating the efficiency of friction and piezoelectric energy harvesting devices. Currently, the following approaches are commonly utilized:

(a) External load, use $P = U^2/R$ to calculate the output power of the devices [126,135].
(b) The output voltage represents the energy storage effect of the devices. The electric energy harvested by the piezoelectric energy harvesting devices are stored in a capacitor or battery through a storage circuit, and the voltage at both ends is directly measured and compared [127–129].
(c) The energy stored by the capacitor is used to show the energy storage effect. The electric energy harvested by the piezoelectric energy harvesting devices is stored in the capacitor through the storage circuit, and the voltage at both ends can be measured. Then, the energy in the capacitor can be calculated by $E = 0.5CU^2$ [129–132,135].
(d) The energy storage effect is shown by the time it takes to charge the battery to its rated voltage. Let the piezoelectric energy harvesting devices continue to work, then detect the voltage at both ends of the battery in the storage circuit and evaluate the strength of the energy storage effect by the time it takes different devices to charge the same battery to the same rated voltage [130–132,135].
(e) Measured directly through the devices. Oscilloscope and current amplifier are used to measure the output voltage and output current, respectively [128].

7. Future Directions

Recently, the development and research of human energy harvesting devices have made many advances in materials and technology applications, structural innovation, and efficiency improvement. However, a notable gap remains between laboratory research and real-life applications. Consequently, in the development of human motion energy harvesting devices, there still exist certain challenges and opportunities, indicating significant potential for future advancement.

7.1. Higher Energy Harvesting Efficiency

Previous research has made advancements in enhancing the energy harvesting efficiency of devices through diverse structural designs (e.g., improvements to the magnetic stack method, optimization of coil arrangement, mixed application of harvesting methods, etc.). However, the material properties of the energy harvesting unit constitute the most fundamental factor affecting the output efficiency of these devices. Various parameters of the material, such as the electromechanical coupling coefficient and piezoelectric coefficient, directly influence the performance of the devices. Therefore, besides establishing a mutual coupling between human motion and device operation through structural design, it is imperative to conduct further investigations into energy harvesting unit materials. Exploring novel materials with superior energy conversion efficiency and achieving higher energy levels with smaller material sizes are crucial for enhancing the energy density of the devices.

7.2. Design of Compound Energy Harvesting Devices

Different forms of energy harvesting possess their own advantages and disadvantages. The combination of multiple energy harvesting forms can be chosen based on the motion characteristics at the energy harvesting site. For instance, by combining the electromagnetic type, which is suitable for extracting rotational motion, with the piezoelectric or friction type, which are ideal for capturing unidirectional swinging motion, it becomes possible to simultaneously harvest energy from different types of motion. Similarly, by combining the friction type, suitable for low-frequency motion harvesting, with the electromagnetic or piezoelectric type, suitable for high-frequency motion, it is feasible to achieve energy harvesting across a broader frequency range. In future research, we can leverage the strengths of various approaches to design composite devices that yield more comprehensive energy harvesting capabilities.

7.3. Effective Storage of Energy

The practical storage of harvested energy can enable more convenient usage for individuals. However, current energy harvesting devices primarily operate in an immediate-use mode without incorporating energy storage capabilities. Consequently, it becomes imperative to design and implement storage circuits that align with the energy characteristics of different harvesting modes. By integrating energy harvesting devices with suitable energy storage circuits, we can achieve effective energy storage, thereby enabling more flexible and stable utilization of the harvested energy.

7.4. A Wider Range of Applications

Human energy harvesting technology presents an immense potential for wearable and MEMS applications. In addition to powering low-power devices like rescue gear and GPS positioning equipment, this technology can also be harnessed in medical fields for activities such as personal health monitoring, flexible sensing that cannot be self-powered, physiological detection, and passive harvesting of comprehensive health data during epidemics. As this technology matures, it is poised to make more contributions to daily human life as well as the advancement of science and technology.

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