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REVIEW PAPER

A Review of Human-Powered Energy Harvesting for Smart Electronics: Recent Progress and Challenges

Salman Khalid[1] · Izaz Raouf[1] · Asif Khan[1] · Nayeon Kim[1] · Heung Soo Kim[1]

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Abstract
Recently, energy harvesting from human motion has attracted substantial research into its ability to replace conventional batteries for smart electronics. Human motion exhibits excellent potential to provide sustainable and clean energy for powering low-powered electronics, such as portable instruments and wearable devices. This review article reports on the piezoelectric, electromagnetic, and triboelectric energy harvesting technologies that can effectively scavenge biomechanical energy from human motion such as, walking, stretching, and human limb movement, as well as from small displacements (e.g., heartbeat, respiration, and muscle movement) inside the human body. Furthermore, various recent designs and configurations of human motion energy harvesters are presented according to their working mechanisms, device compositions, and performances. In order to provide insight into future research prospects, the paper also discusses the limitations, issues, and challenges of piezoelectric, electromagnetic, and triboelectric energy harvesting technologies for the development of smart electronics.

Keywords Piezoelectric energy harvesting · Electromagnetic energy harvesting · Triboelectric energy harvesting · Human powered · Smart electronics · Wearable devices

List of Symbols

D	Electric displacement
d	Piezoelectric coefficient
σ	Stress
$\in$	Permittivity
s	Elastic Compliance
E	Electric field Intensity
ε	Strain
V	Voltage
N	Number of turns
θ	Total magnetic flux
t	Time
B	Magnetic field
Ai	Area of ith coil
V_{tr}	Initial voltage between the two electrodes
ε_0	Vacuum permittivity
d_{tr}	Interlayer distance
S_{tr}	Surface area
I_{tr}	External electrodes

✉ Heung Soo Kim
heungsoo@dgu.edu

[1] Department of Mechanical Robotics and Energy Engineering, Dongguk University-Seoul, Pil-dong, Jung-gu, Seoul 04620, South Korea

1 Introduction

With the rapid growth in miniaturized electronics, smart electronics such as smart watches, smart shoes, smart textiles, and smart wearables for biomedical monitoring have gained much importance with the aim of minimizing the need for external power sources such as batteries [1]. However, there is considerable development executed in enhancing the battery storage, as this system still requires regular charging and a replacement process which significantly narrow down their applications [2]. Therefore, a continuous, clean, and sustainable energy source for powering portable and wearable electronics is required. The most fundamental and ideal solution is to scavenge energy from the ambient environment and transform it into electricity [3]. Solar and wind can provide renewable and clean energy, but they cannot deliver continuous power because of their dependence on climatic conditions [4]. By contrast, human motion is present everywhere, exhibiting great potential to generate endless, clean, and sustainable biomechanical energy for smart electronics [5].

Human biomechanical motions such as finger movement, walking, running, typewriting, and even minute displacements inside the human body such as lung motion, heartbeat, and muscle contraction possess an abundant amount of waste energy that can be harvested [6]. Among them, lower limb motion such as swinging of the legs can deliver maximum power because of their higher torques than movements of other body parts [7]. However, harnessing energy from human motion is quite complex and challenging because of the multidimensional movements and ultra-low frequency of human motion [8]. Therefore, energy harvesting technologies that can effectively harvest human motion energy are needed. Progress in the development of self-powered wearable electronics considerably relies on the performance of energy harvesting technologies [9].

Piezoelectric [10], electromagnetic [11], and triboelectric [12] are the most common technologies used to harvest biomechanical energy from human motion. Piezoelectric materials work on the principle of the piezoelectric effect, i.e., the property of the material to generate electricity upon mechanical deformation [13]. These materials generally fall into transverse, longitudinal, and piezotronic working modes [14, 15]. Various researchers have used these working modes to harvest energy from human in vitro and in vivo motion for powering smart wearable devices such as smart shoes, smart skin, smart textiles, implantable devices, and biomedical monitoring devices. Similarly, electromagnetic materials based on human motion energy harvesting are well known for their higher power outputs. Electromagnetic energy harvesting devices work on Faraday's law of electromagnetic induction, i.e., the property of the material to induce electric current when passing through the magnetic field [16]. Depending on their mechanism, these materials can be further classified into the rotary, oscillatory, and hybrid energy harvesters [17]. Rotary harvesters usually use a gear train and turbines because of their high power output requirements [18]. Oscillatory harvesters use the mass-spring-damper system that generally works in low frequency excitations with low power outputs, and hybrid electromagnetic harvesters use eccentric rotors to couple kinetic energy produced by human motion [19, 20]. A lot of research has examined human motion-based electromagnetic energy harvesters for self-powered wearable electronics, but due to their bigger sizes and lack of miniaturized designs, these harvesters are usually coupled with other materials such as piezoelectric and triboelectric materials to be integrated into wearable electronics [21]. Finally, the most recent and advanced technology for human motion energy harvesting is triboelectric energy harvesting, which operates on the well-known phenomenon called triboelectrification in which materials become electrically charged upon frictional contact [22]. The relative displacement between electrically charged materials results in the generation of electricity. Four types of working modes have been proposed, depending upon the type of relative motion between the two triboelectric materials and the position of the electrode. These working modes are the vertical contact separation mode [23], sliding contact mode [24], single electrode mode [25] and freestanding mode [26]. Triboelectric energy harvesters are the most commonly used human motion-based energy harvesters because of their nanoscale design and high-power outputs. Various types of smart electronics using triboelectric harvesters have been examined in the literature, with smart textiles, smart skin, and health monitoring wearable devices being quite common among them [27].

In this study, we comprehensively reviewed human-powered energy harvesting technologies for smart wearable electronics (Fig. 1) using piezoelectric, electromagnetic, and triboelectric materials. The working principles and operating modes of the piezoelectric, electromagnetic, and triboelectric energy harvesters are discussed along with recent designs and configurations for energy transduction from human body motion. The paper also discusses the issues and challenges associated with the said energy harvesting technologies (e.g., ultra-low frequency of human motion, multimodal movement of human joints) for the development of self-powered smart electronics. This article aims to provide insight into the current state-of-the-art of human-driven miniature energy harvesters using piezoelectric, electromagnetic, and triboelectric materials, along with future research directions.

2 Piezoelectric Energy Harvesting by using Human Motion

Energy harvesters utilizing mechanical and vibration energy sources are promising technologies for the successful implementation of self-powered energy systems in severe and remote environments as well as living organisms, such as animals and the human body [28]. Recently, researchers have paid much attention to developing biocompatible and flexible devices that can harvest energy from both human in vitro and in vivo motion [29]. Piezoelectric devices have

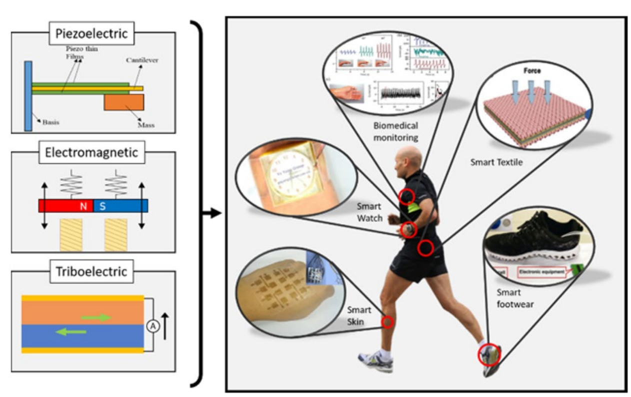

Fig. 1 Human-powered energy harvesting technologies for smart electronics

gained much importance in the field of biomechanical energy harvesting technologies due to their simple structure and ease of utilization [30, 31].

2.1 Working Principle

Piezoelectric energy harvesting is perhaps the most widely reviewed technology over the past decade [32]. The Curie brothers first identified Piezoelectricity in 1880 [33]. Piezoelectricity is the property of a material to generate electricity upon mechanical deformation. In general, constitutive equations of the linear piezoelectric effect are defined as direct and indirect effects [34].

$$D = d\sigma + \in E \tag{1}$$

$$\varepsilon = s\sigma + dE \tag{2}$$

where ε and σ are strain and stress, respectively; E and D are the electric field intensity and electric displacement, respectively; d, ∈, and s are piezoelectric coefficient, permittivity, and elastic compliance, respectively. Equation (1) describes the direct effect, i.e., the conversion of mechanical energy to electrical energy. By contrast, the converse effect, as displayed in Eq. (2), signifies the transformation of electrical power to mechanical deformation. For further explanation, the direct effect is the tendency of particular crystalline materials, e.g., Rochelle salt, barium titanate, and quartz, that produce electrical power when applied pressure or mechanical force. By contrast, in the converse effect, these materials experience deformation upon being applied an electric field [35].

One of the fundamental limitations of linear piezoelectric vibration energy harvesters (PVEHs) is their narrow bandwidth of excitation frequencies compared to non-harmonic and broadband or time-varying characteristics of vibrations from human body motion. Nonlinear PVEH have been proposed to overcome the limitation of linear PVEHs [36, 37]. In general, Duffing equations and Kirchhoff's law are employed to describe the dynamic behavior of nonlinear PVEHs as given by [38, 39]

$$m\ddot{x} + c_{d,m}\dot{x} + dU(x)/d(x) - \vartheta v = F_{ext} \tag{3}$$

$$U(x) = 1/2(k_1x^2) + 1/4(k_3x^4) \tag{4}$$

$$\vartheta\dot{x} + C_P\dot{v} + v/R_l = 0 \tag{5}$$

where, m and $c_{d,m}$ are equivalent mass and damping of the system, respectively. The variable x refers to the displacement of the mass and v is the voltage generated in load resistance R_l. The terms k_1 and k_3 accounts for linear and nonlinear restoring and the quantity U(x) is the mechanical potential energy of the vibrating system. C_P is the equivalent capacitance of the piezoelectric material, ϑ is the equivalent electromechanical coupling coefficient, and F_{ext} is the external excitation force.

Piezoelectric materials generally fall in two categories, i.e., piezoceramics and piezopolymers. Piezoceramics are usually brittle, but they possess large electromechanical coupling constants and have high energy conversion rates. On the other hand, piezopolymers are flexible, but they have drawbacks such as low electromechanical coefficients and low energy conversion rates contrast to piezoceramics. Table 1 summarizes the material properties of piezoceramics (PZT-5H, PZT8) and piezopolymer (PVDF).

2.1.1 d_{33} Mode (Transverse Mode)

Depending on the working principle, piezoelectric energy harvesters (PEHs) can generally be categorized into three types: d_{33} mode, d_{31} mode, and piezotronic mode [43, 44]. Piezoelectric devices are normally used as layered beam structures, which consist of several layers of piezoelectric, elastic, conducting, or insulating materials. If an electric potential is applied between the conducting layers, an actuation force is produced in the piezoelectric layers. In general, d_{31} and d_{33} are the two piezoelectric modes of operation in use. Their names are chosen according to the associated piezoelectric constant. The indices indicate the direction of stress–strain components and the electric field.

The standard form of a piezoelectric material with d_{33} working mode is shown in Fig. 2a. Stacked piezoelectric materials use d_{33} working mode for harvesting energy. Herein, multiple piezoelectric thin films in parallel electrical connection and serial mechanical connection are layered upon each other so as to create a piezoelectric stack, as shown in Fig. 2b. As thin films are mechanically connected in series, the total displacement of the piezoelectric stack actuator is the product of the total number of films times the

Table 1 Piezoelectric characteristics [35, 40–42]

Material Properties	Unit	PTZ-5H	PZT-8	PVDF
d_{31}	m/V	-274×10^{-12}	−97	18–24
d_{32}	m/V	-274×10^{-12}	−97	2.5–3
d_{33}	m/V	-593×10^{-12}	225	−33
d_{15}	m/V	741×10^{-12}	330	
Relative permittivity e_{33}		3400	1000	10
Poling field dc	kV/cm	12	5.5	–
Curie temperature	°C	193	300	–
Density	kg/m^3	7500	7600	1800
Open circuit stiffness E_{11}	GPa	62	87	–
Open circuit stiffness E_{13}	GPa	48	74	–
Tensile strength (static)	MPa	75.8	75.8	–
Tensile strength (dynamic)	MPa	27.6	34.5	–
Dielectric breakdown	kV/cm	20	–	–

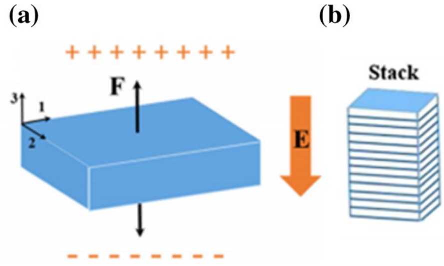

Fig. 2 d_{33} Mode **a** working mechanism, **b** piezoelectric stacks [45]

movement of each film. Each piezo element is intended to produce optimum energy under the standard strain of 0.1% [46]. In high loading cases, a piezoelectric stack composed of a large number of piezoelectric thin films in d_{33} mode is suitable for operation. This design configuration is easy to assemble and can potentially reduce the number of fabrication steps [47] and the amplification of charge production [48]. Sodano et al. [49] introduced the mechanically amplified strap buckle for a backpack using a piezoelectric stack actuator for energy extraction, and observed the peak output power of 0.4 mW. Guido et al. [50] reported biocompatible energy harvesting from human motion by stacking thin films of aluminum nitride with a peak voltage of 0.7 V and electrical power of 0.2 μW. Kim et al. [8] improved a flexible energy harvester for multi-directional input forces made of PDMS and PVDF films with the peak generated output voltage of 1.75 V. Zhao et al. [51] recommended the use of a multilayer PVDF to design PEHs from mechanical energy in shoes originating from human motion with the power output of 1 mW. Similarly, Cao et al. [52] developed a shoe-inserted harvester with a zig-zag structural design composed of two stainless steel layers and one PVDF film. This design was implemented on a human running on a treadmill at 6 km/h, producing a peak output voltage of 5.032 V. Xu et al. [53] designed an energy harvester for human footsteps during walking based on the force amplification mechanism to amplify the force applied on the piezoelectric stack and examined the high output power as compared to existing designs. Zuo et al. [54] used the same force amplification mechanism as that shown in Fig. 3, and fabricated footwear energy harvester consisting of several piezoelectric stacks and two aluminum plates for walking at different walking speeds, and observed a maximum power output of 28 mW. Similarly, different studies have been done on force amplification mechanism in order to maximize the power output in piezoelectric energy harvesting devices [55–58].

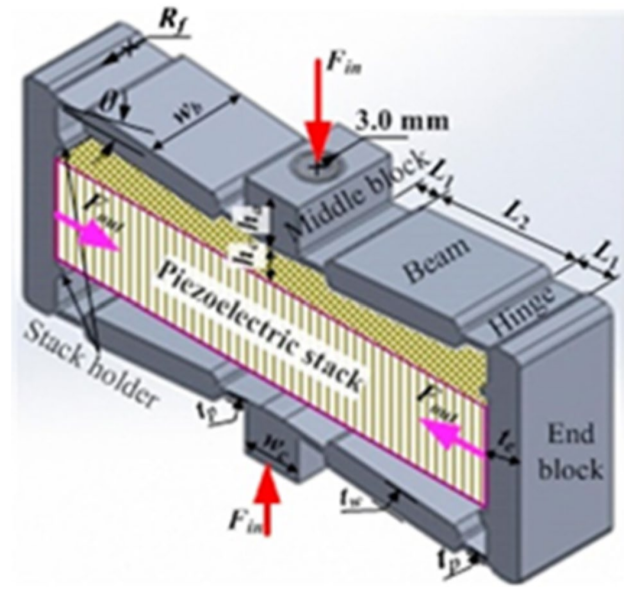

Fig. 3 Force amplification mechanism with piezoelectric stack [54]

2.1.2 d_{31} Mode (Longitudinal Mode)

Generally, in d_{31} mode, piezoelectric plates or films are fixed upon supporting structures. In d_{31} working mode, the transducer incorporates a piezoelectric layer inserted between the top and bottom electrode (TBE) layers. An electric field is employed in the vertical direction, which is used to produce a stress/strain along the horizontal direction, as shown in Fig. 4. These structures are of simple designs, and they can produce homogenous field inside the active layers [43]. d_{31} modes have been widely studied using cymbals, unimorphs, and bimorphs. Granstrom et al. [59], using d_{31} mode piezoelectric energy harvesting, reported the development of a piezoelectric shoulder strap by replacing the conventional fabric strap with a polyvinylidene fluoride (PVDF) strap, and generating an output power of 45.6 mW.

Turkmen et al. [41] developed a cymbal type piezoelectric energy harvester, as shown in Fig. 5a, using PZT-5H piezoceramic and a frame made of steel as a supporting structure. They used this energy harvester to design the sole of a shoe and investigated the power output for different human weights, and ultimately generated a peak output power of 1.43 mW. Lim et al. [60] studied the optimum orientation

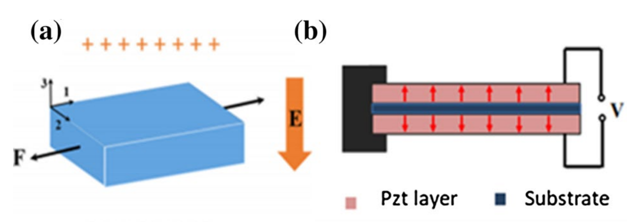

Fig. 4 d_{31} Mode **a** working mechanism, **b** schematic diagram of piezoelectric layer fixed upon supporting structure using d_{31} working mode [45]

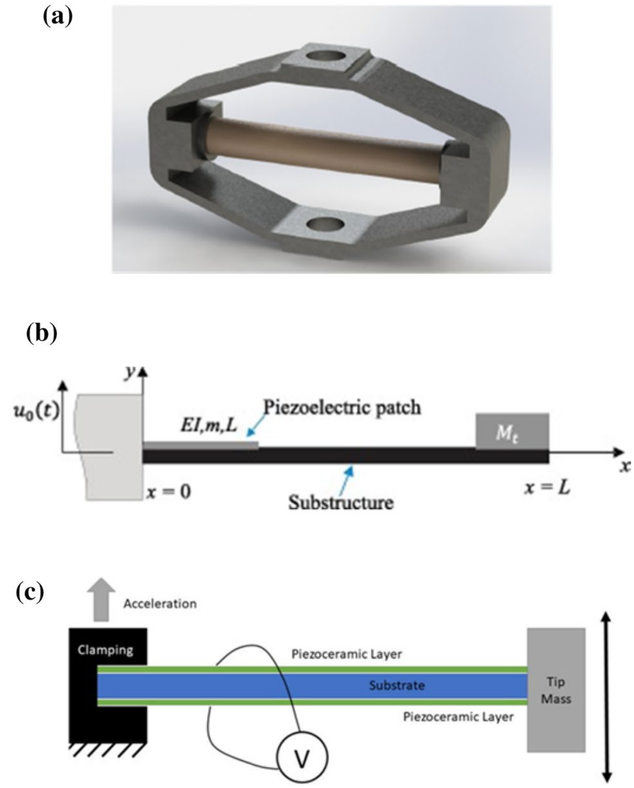

Fig. 5 PEH configurations for d_{31} working mode **a** Cymbal, **b** Cantilever with PZT patch attached, **c** Bimorph cantilever beam [41] [60, 62]

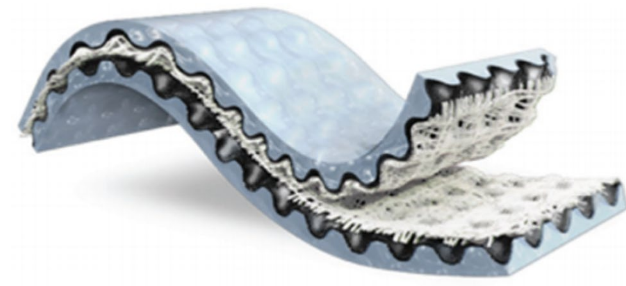

Fig. 6 Schematic representation of stretchable piezoelectric nanogenerator (S-PENG) [66]

of PEH using a cantilever beam with a piezoelectric patch design, as shown in Fig. 5b, to extract energy from walking, and found a peak power output at 70° orientation of PEH regarding the coordinate system connected to the leg of a human walking on a treadmill. Similarly, Saida et al. [61] used the unimorph cantilever design to harvest energy from the human body. Yang et al. [62] used a bimorph cantilever design, as shown in Fig. 5c, to scavenge energy from human hand motion by using a wearable device, and generated an output power of 50 µW from hand motion.

2.1.3 Piezotronic Mode

With advancements in nanotechnology, the need for nanoscale piezoelectric energy harvesting devices to power nanoscale systems and for performance enhancements has dramatically increased [63]. Piezotronic effect emerged with the discovery of ZnO nano wires with n-type conductivity [64]. For the development of self-powered electronics, researchers have extensively used ZnO based Piezoelectric nanogenerators (PENGs) [1]. The basic working principle of the piezotronic is the formation of a Schottky barrier at the interface of the piezoelectric nanowire and the electrode that regulates the flow of electron, induced due to the piezoelectric potential [44]. Guo et al. [65] recently reported a piezoelectric nanogenerator using a ZnO nanorod pattern textile, and examined a peak current and output voltage of 20 nA and 4 V, respectively, from human motion. Siddiqui et al. [66] fabricated a wearable piezoelectric nanogenerator, as shown in Fig. 6, by using the stacked nanofibers mat and graphite electrode to harness energy from human walking motion, and demonstrated the peak open circuit voltage (OCV) of 10.1 V. Moreover, several designers have fabricated PENGs using various piezo nanofibers and electrodes to improve durability, flexibility, and biocompatibility for human-powered energy harvesting [67–69].

2.2 Recent Designs and Applications

In this section, the most recent research regarding different possible configurations and designs of piezoelectric energy harvesting using human (in vitro and in vivo) motion for self-powered and wearable electronics is discussed.

2.2.1 Smart Footwear

Designing new and different configurations of piezoelectric footwear, such as shoes and slippers, has been quite common over the last decade [70–72], as human walking provides enough endless energy with which to power portable and wearable devices. However, due to the different complexities involved in human motion, multiple authors are still addressing this technology to develop more durable, biocompatible, and flexible footwear. Humans always tend to prefer movement patterns that minimize energy expenditure, and any change in the locomotion results in the addition of a metabolic cost. In order to address this problem, Xia et al. [73] developed angle-sliding shoes that can harvest energy without increasing metabolic cost. Cha et al. [74] modified the slippers by removing the heel counter and focused on harvesting energy from the bending of the sandals. Dong et al. [75] proposed smart shoes with the capability of energy storage by the usage of capacitor that can simultaneously work as a harvester and sensor by using same PEH hardware and optimize the sensing by applying a filter algorithm. Usually, stacked piezoelectric harvesters can bear large force excitations and be used for higher power outputs. Zuo et al. [54] developed a compressive force amplification frame composed of piezoelectric stacks, and fastened it between aluminum plates by bolts for the further improvement of conversion energy efficiency. A footwear harvester inserted in the heel of shoes used more space and made full use of the vertical force available upon foot strike. Dynamic force measurement was also considered by positioning a force sensor inside the aluminum plates, as shown in Fig. 7a, and installing them into the heels of the shoes, as displayed in Fig. 7b. Figure 7c depicts the experiment conducted on a treadmill to optimize the power output by considering different external resistive loads.

Cao et al. [76] demonstrated that for harvesting energy form human motion, a nonlinear bistable harvester with time-varying potential outperformed the corresponding linear and monostable harvesters. Wang et al. [77] investigated that an optimum load resistance could maximize the output power of a nonlinear tristable energy harvester from human lower-limb motion. Li et al. [78] reported a non-linear low-frequency piezoelectric energy harvester with a truss mechanism for the amplification of applied force on piezoelectric element and an amplitude limit mechanism for inducing impact forces. The proposed design showed an open-circuit voltage of 83.3 V and maximum power output of 32 mW at resonant frequencies of 3.3 and 6.09 Hz, a bandwidth of 4.2 Hz out of a sweep frequency domain of 7.5 Hz.

2.2.2 Smart Textile

Smart textiles are a kind of wearable technology that hold the potential to bring about a massive revolution in the field of wearable technology. Piezoceramics possess excellent dielectric and piezoelectric properties, but they are brittle and hard, making them unsuitable for textile applications. Designers are working to create more flexible and skin-friendly textiles for user comfort. Beeby et al. [79] recently proposed a flexible piezoelectric nanocomposite-based textile that can harvest mechanical energy under compressive and bending forces and possesses higher dielectric and piezoelectric properties. Christine et al. [80] developed 100%PVDF woven (2-D and 3-D) structures using the melt spinning process in order to optimize the output voltage, and studied the impact of compression pressure on the fabrics. Similarly, Guo et al. [65] fabricated a flexible piezoelectric nanogenerator-based textile composed of two layers of silver coated on Nylon fabric fixed symmetrically on the top and bottom of ZnO rod arrays, as shown in Fig. 8a. This device can extract energy when attached to the finger and palm of a human, as shown in Fig. 8b.

2.2.3 Smart Skin

Lately, self-powered e-skin technology has demonstrated significant potential in self-powered sensors [81], health monitoring [82], wearable devices [83], and so on. By contrast, piezoelectric nanogenerators (PENG) have come to light as a promising green energy harvesting technique. PVDF with merits such as high flexibility, high piezoelectric constant, and low impedance shows consistency with human skin [84] and is currently used to extract energy from human motion energy. Wang et al. [25] reported a flexible, transparent, and self-powered single electrode PENG based on PVDF nanofiber that senses steady state pressure and temperature on a single unit. Single electrode PENG overcomes the weaknesses of a Triboelectric nanogenerator (TENG) by simultaneously detecting pressure and cold/heat. Figure 9 represents the structure and properties of self-powered e-skin. Figure 9a shows that smart skin fits well with skin, Fig. 9b describes the diameter and distribution of PVDF nanofiber. Figure 9c outlines the good transparency properties of e-skin, and Fig. 9d expresses that the transmittance of e-skin with ITO electrode is 70%. Similarly, Zhengzhu et al. [85] fabricated a self-driven PENG by using a PVDF

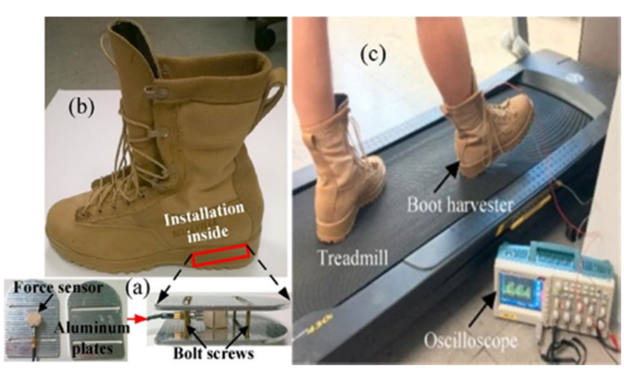

Fig. 7 Smart shoes **a** force sensor installed on the aluminum plates, **b** installation location, **c** treadmill experiment [54]

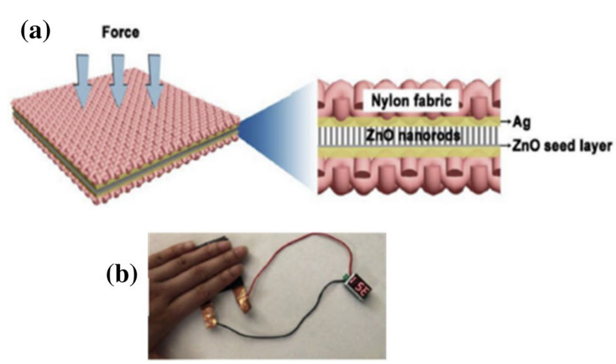

Fig. 8 Smart textile **a** structure and schematic design of textile based PENG, **b** powering PENG by palm pressing [65]

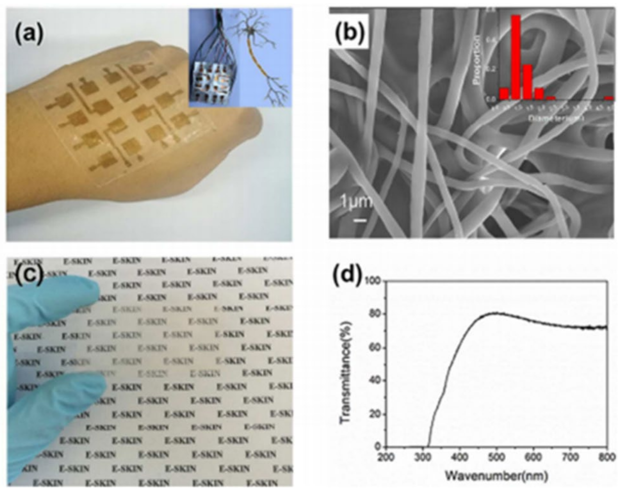

Fig. 9 Structure and properties of e-skin **a** e-skin shows good fit with skin, **b** SEM image of PVDF nanofiber, **c** transparency of e-skin, **d** transmittance of e-skin [25]

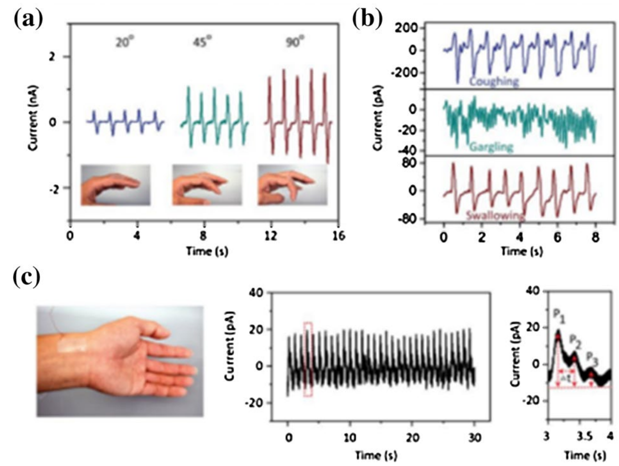

Fig. 10 Physiological monitoring applications of PENG **a** PENG attached onto human finger bent with different angles and corresponding output current, **b** PENG monitoring the human throat activities, **c** PENG monitoring artery pulse signal [91]

nanofiber patterned electrochemical supercapacitor with both energy harvesting and storage applications. Further various authors have worked on self-powered e-skin based on e-skin, and more literature about this technology can be found in the references [86–88].

2.2.4 Implantable Devices and Biomedical Monitoring

Traditionally implantable medical instruments, such as cardiac defibrillators and deep brain neurostimulators, use battery power to work. However, due to the limited capacities of batteries as well as their size restrictions, the lifetime of implantable devices is limited. Therefore, it is crucial to research sustainable sources to power such devices. The human body itself is a source of abundant energy, with an example being the movement of internal organs (e.g., heartbeat, systolic/diastolic deformation, and lung motion) which can produce sustainable energy [89]. Recently, piezoelectric energy harvesters are being used to harvest energy from the internal organs of animals scalable to human size [90]. Furthermore, piezoelectric devices have sensing applications, such as health and physiological monitoring. Wu et al. [91] reported the integration of selenium nanowires into wearable devices to convert intangible time variant movements (radial artery pulse and vocal movement) of the human body into electrical signals, and pointed to the potential of such devices for wearable self-powered biomedical devices, as shown in Fig. 10. Figure 10a presents the application of PENG attached on the finger for detecting the motion of the human finger and corresponding current output with different bend angles of a finger. PENG attached to the throat can identify different vocal movements such as coughing, gargling, and swallowing, as shown in Fig. 10b. Figure 10c describes the real-time sensing ability of PENG.

2.3 Issues and Challenges

As discussed previously, piezoelectric energy harvesting technology from human motion exhibits excellent potential for powering low powered electronics and wearable devices; however, this field is still faced with many challenges and issues to address. The first challenge encountered by piezoelectric harvesting devices is the ultra-low frequency of humans, which is around 1 Hz [92]. However, the operating bandwidth of PEHs is quite high, which makes human motion unfeasible for PEH [60]. In addition, the motion range of humans is usually much higher than the predetermined device size, and so resonant devices cannot render the advantage of powerful magnification. The operating excitation frequency must fall in the resonant frequency range of harvester so as to obtain the best results. Generally, the frequency up conversion technique [93] is used to overcome this hurdle. Mostly, mechanical plucking mechanism by using piezoelectric bimorph was used for frequency-up conversion that could generate enough energy from human limbs motion to power low-powered electronics. However, these devices showed some drawbacks such as reduced longevity due to the direct contact between bimorph and plectra and noise. To overcome such challenges Yang et al. [94] designed a prototype for piezoelectric knee-joint energy harvester by replacing mechanical plucking by the non-contact magnetic plucking device to perform the frequency-up conversion and achieve a power output of 5.8 mW at the knee joint motion of 0.9 Hz. Further, Fu et al. [95] developed a low-speed rotational energy harvester with the ability to extract energy using piezoelectric transduction via magnetic plucking frequency-up conversion. The energy harvester exhibited wide bandwidths at low frequency with the peak power output of 20 μW proving to be much suitable for rotational energy harvesting situations such as human motion.

Human motion involves multidimensional motion, such as bending, stretching, and sliding, in addition to linear vibrations [8]. Human limbs produce complex movements during walking, making it difficult for linear PEHs to extract power from multidimensional motion. Therefore, in order to solve this challenge, Fan et al. [7] developed a harvester based on a cantilever beam design using a sleeve, ferromagnetic ball, and magnets fixed at both ends. This harvester was shown to be capable of obtaining energy from lower limb motion and vibrations of a human body. The other main issue for the before-mentioned harvesters is flexibility, biocompatibility, and biodegradability. Ceramic piezoelectric materials are rigid and brittle, making them unsuitable for human motion applications. Therefore, Luo et al. [96] mounted a lightweight, flexible polypropylene ferroelectric material in shoe soles to solve the flexibility problem. Many piezoelectric materials are not favorable for integration in wearable devices due to their toxic lead content. An alternative to such materials is lead-free piezoelectric harvesters having properties similar to conventional piezoelectric materials. Zhao et al. [97] used a wool-keratin-based biocompatible piezoelectric nanogenerator in the wearable electronic application. Kim et al. [98] fabricated silk fibroin-based lead-free green composite utilizing ferroelectric nanoparticles. Likewise, multiple authors have published biodegradable and biocompatible piezoelectric energy harvesters [99–102]. Piezoelectric energy harvesters can effectively harvest human motion energy by solving the narrow band issues of such devices. The advancement in microfabrication techniques in the past decade leads to the development of microscale piezoelectric energy harvesters such as the fabrication of MEMS PEEHs. Further progress in nanotechnology has enabled the researchers to develop ZnO nanowire which is much popular piezoelectric material in nano piezoelectric energy harvesters and improved the performance and integration issues. The continuous development in nanotechnology will enable the feasibility of PEEHs in human motion based energy harvesting in the future.

3 Electromagnetic Energy Harvesting (EMEH) by Using Human Motion

Electromagnetism has been used to harvest energy since Faraday's significant discovery in electromagnetic induction [3]. As the interest in human motion-based energy harvesting has grown, multiple designs of electromagnetic energy harvesters (EMEHs) have been proposed to power wearable and self-powered electronics [103, 104]. This section describes the working principle, recent progress, and challenges in EMEH.

3.1 Working Principle

The basic law of the electromagnetic energy harvester is based on the principle of electromagnetic induction. In 1831, Faraday noticed that the potential difference is produced at both ends of the coil, as it moves through the magnetic field. In addition, the voltage induced in the coil is proportional to the time rate of change of magnetic flux [105].

$$V = N\frac{d\emptyset}{dt} \tag{6}$$

where N is the number of turns in a coil and Ø is the total magnetic flux, with t being the time. Total flux Ø is further described as

$$\emptyset = \sum_{i=1}^{N} \int_{Ai} BdA \tag{7}$$

Ai is the area of ith coil and B is the magnetic field. Energy harvesters utilize relative motion of the coil (conductor) and a magnet to generate electricity. There are two modes of operation in electromagnetic energy harvesting. In the first mode, the coil moves perpendicular to the magnetic field, resulting in a change of the coil area, while the intensity of the magnetic field across the conducting coil remains uniform. In the second mode, the coil moves along the direction of the magnetic field, followed by a change in the magnetic field intensity and uniform coil area. Depending on the kind of mechanical motion involved, EMEHs are usually classified into three working modes [17]. Rotational energy harvesters transform the rotational mechanical displacement into electrical energy. Oscillatory generators are generally designed as mass-spring-damper systems that convert relative motion between the coils and magnets to obtain electricity; by contrast, hybrid generators translate linear motion into rotational movement by using an eccentric rotor.

Numerically, electromagnetic energy harvesters could be modeled as resonant linear generators for a narrow bandwidth of excitation frequencies or non-linear harvester for a broad band random excitation. A comparison of the classical resonant single frequency linear models and multi-frequency nonlinear models could be found in these references [106–108]. In general, the dynamic behavior of a linear EMEH is described by linear spring stiffness and linear total damping as given by

$$\mathrm{m\ddot{x} + c_T\dot{x} + kx = F_{ext}} \tag{8}$$

where, x, ẋ, ẍ respectively quantify the relative displacement, relative velocity and relative acceleration between the permanent magnet and the coil. The term m, c_T and k denote the mass, linear damping and linear spring stiffness of the system, respectively. F_{ext} denotes the external excitation applied to the system. Total damping of the harvester is a combination of the mechanical and electrical damping (i.e., $c_T = c_m + c_e$).

The general form of the governing equation of motion of a nonlinear EMEH is described by nonlinear damping and nonlinear spring stiffness as given by

$$m\ddot{x} + \left[c_T\dot{x} + c_T\alpha D(\dot{x})\right] + [kx + k \cdot N(x)] = F_{ext} \tag{9}$$

Herein, the nonlinear damping of the harvester is comprised of linear damping component $c_T\dot{x}$ and nonlinear damping component $c_T\alpha D(\dot{x})$. The term α and $D(\dot{x})$ denote the scaling factor and nonlinear function, respectively, and account for nonlinearity in the damping of the harvester. The stiffness of the harvester is comprised of linear component kx and nonlinear components $k \cdot N(x)$.

3.1.1 Rotational EMEHs

Rotational EMEHs usually consist of a magnet, coils, and speed shifting devices like gear trains and turbines because of the high power output requirements [109]. Lately, designers have used such harvesters to extract energy from human motion. Liu et al. [110] proposed a nonresonant rotational energy harvester (REH) comprised of the rotor magnet, stator, and magnetic coils embedded in a casing without using any complex transmission mechanism, as shown in Fig. 11a. If attached to the arm or ankle of a human, the rotor magnet rotates clockwise or anticlockwise around the stator magnet, as shown in Fig. 11b. The physical mechanism of REH, as shown in Fig. 11c, demonstrates the rotation of the rotor magnet under externally applied force F. A treadmill experiment has demonstrated various power outputs of a human at different speeds with a maximum power output of 10.4 mW at a driving frequency of 8 Hz and load resistance of 100 Ω. Similarly, Lin et al. [111] introduced nonresonant REH using a Neodymium Iron Boron rotor and stator magnets that formed a higher pair theoretical line contact without mounting any bearing or shaft structure, and built a wristwatch prototype energy harvester with a maximum measured output voltage of 1.92 V and power density of 0.92 mW/cm^3. Zhu et al. [112] developed a compact in-shoe energy harvester consisting of a wave spring and rotational electromagnetic generator, and recorded a peak power output of 1.6 mW in each step of a walking person. Mehdi et al. [18] fabricated a wearable micro rotary electromagnetic generator for converting human motion to electrical energy. The two main features of small size and the use of a pendulum without a gear were introduced in the design and generated a maximum power output of 416.6 μW during human walking.

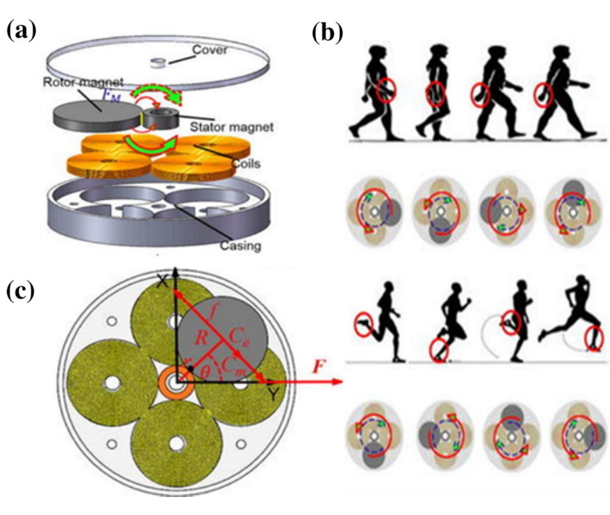

Fig. 11 Working of REH **a** structure of REH, **b** clockwise and anticlockwise rotation of REH attached to wrist and ankle does, **c** physical model of REH with rotation of rotor magnet [110]

3.1.2 Oscillatory EMEHs

The oscillatory harvester uses a mass-damper system that usually works in a lower frequency than other EMEHs. However, due to the restricted range of mass motion inside the tube, the power outputs of these devices are low, particularly for low-frequency excitations such as those of the human body. Various designers have designed such energy harvesters for human motion. Wang [113] proposed a magnetic-spring design for energy harvesting. The device consisted of a hollow tube with magnets fixed at opposite ends. Magnetic mass moves inside along the horizontal direction due to the repelling forces of end magnets, as shown in Fig. 12a. Further, a prototype was built for human walking motion using 3D printing technology with solenoid coils wrapped around the tube as shown in Fig. 12b and generated a maximum power output of 10.6 mW at a walking speed of 8 km/h. Likewise, Ylli et al. [114] developed an oscillator energy harvester consisting of copper wire coils, through which a magnet moved freely and employed the generator in a shoe sole with a maximum power output of up to 4.13 mW. Halim et al. [115] demonstrated a miniaturized electromagnetic energy harvester using flux guided magnetic stacks

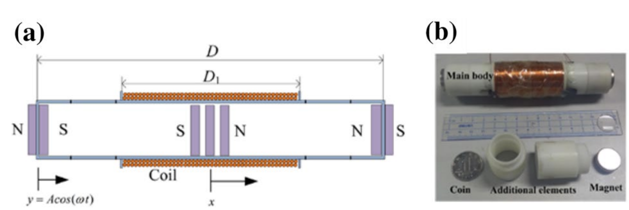

Fig. 12 Oscillator energy harvester **a** schematic of proposed harvester, **b** prototype [97]

instead of a single magnet to scavenge energy from human motion to power self-powered electronics with an average generated output power of 203 µW. Anjum and his team [116] developed a harvester capable of harvesting energy at broader bandwidths and fabricated a prototype to exploit human motion-based energy with a peak induced voltage of 3800 mV at a resonant frequency of 20 Hz. Zhang et al. [117] used microfabricated flexible coils in his design for low-frequency vibrations that can harvest energy from human motion up to 4.3 mW at a resonant frequency of 5.5 Hz.

3.1.3 Hybrid EMEHs

As mentioned previously, the power output of linear motion-based energy harvesters is low, so to overcome this obstacle, designers have utilized rotational inertial mass that uses an eccentric rotor structure to couple kinetic energy produced by human body motion (during running, walking, and stretching) into the transducer element [19]. Halim and his team [118] recently designed a sprung eccentric rotor structure to scavenge power from a driven pendulum that mimics the motion of a human arm during walking. The improved configuration of the rotor magnified the output energy harvested from low-frequency excitations, such as human walking or running, and recorded a maximum power output up to 61.3 µW at 1 Hz frequency. Figure 13a shows the elements of the energy harvester that includes a dual eccentric rotor with magnetic poles. Figure 13b presents the prototype of the fully modeled energy harvester. Qian et al. [119] proposed the analytical model for a sprung eccentric rotor for human motion energy harvesting and examined the average output power of 478 µW. Further, Miyoshi et al. [120] proposed a hybrid energy harvester using thin eccentric mass and a metal ball bearing for rotational support, and used this prototype to extract energy from the arm swinging motion with the peak output power of 80 µW. Further literature on such energy harvesters can be found in the Ref. [121].

3.1.4 Hybridized Electromagnetic Energy Harvesters

There are three primary mechanisms (piezoelectric, electromagnetic, and triboelectric) used to convert biomechanical energy into electricity according to the literature. However, the power output of such small energy harvesters is low and has to operate under low frequency in order to harvest energy from human motion for wearable electronics. Electromagnetic harvesters usually show higher power outputs than other piezoelectric and triboelectric harvesters, but it is complicated to miniaturize and challenging to integrate into wearable devices [122]. Therefore, researchers have developed a hybridized electromagnetic energy harvester that can fulfill high performance requirements due to the combined properties of electromagnetic, piezoelectric, and triboelectric mechanisms for human body motion energy harvesting. Liu et al. [123] fabricated an energy harvester hybridizing electromagnetic and triboelectric mechanisms to harvest human energy. Figure 14a shows an exploded view of the triboelectric energy harvester (TEEH) with a symmetrical top and bottom. Each part consists of two electrodes connected to the substrate. Similarly, EMEH comprised a magnet in a cylindrical structure with copper coils wrapped around the structure, as shown in Fig. 14b. Further, these two devices are then assembled to form a hybridized electromagnetic energy harvester, as shown in Fig. 14c. Figure 14d shows

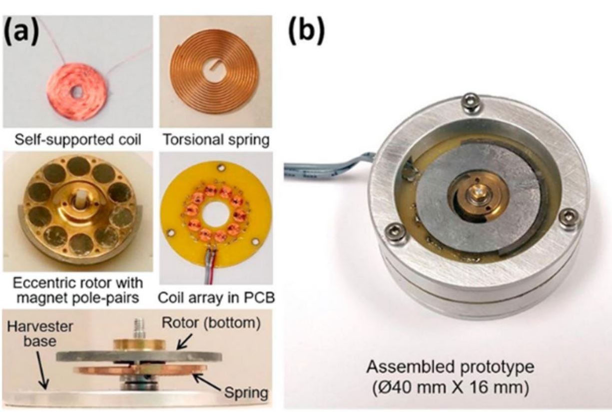

Fig. 13 Hybrid energy harvester **a** elements of energy harvester, **b** fully assembled prototype [118]

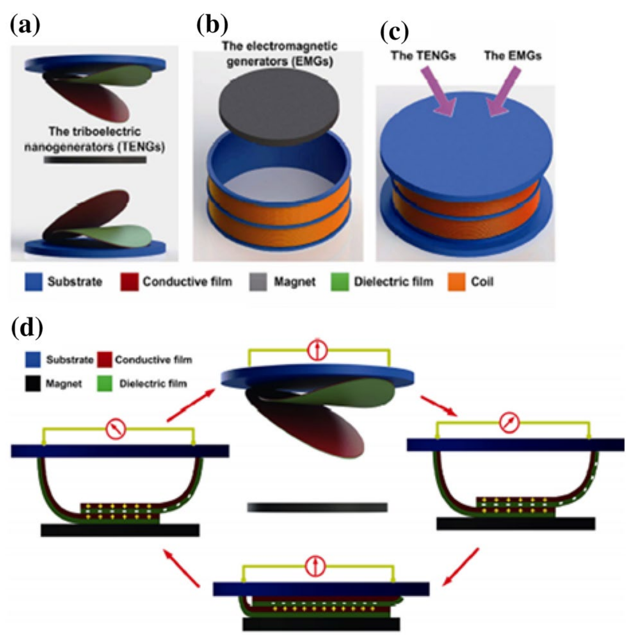

Fig. 14 Structural view and working mechanism **a** split view of TEEH, **b** split view of EMEH, **c** assembled diagram, **d** working mechanism of hybrid device [123]

the working mechanism of the hybrid harvester. TENG uses a round film with two sides; one is PVC fabric, and the other one is conductive. These two films are stacked on the substrate at both the top and bottom ends. With the to and fro motion of the magnet, these films continuously touched each other, thus enabling electrons to move between the conductive surfaces, resulting in the creation of electric power. Moreover, several authors have designed hybrid electromagnetic devices for wearable and self-powered devices [124].

3.2 Recent Progress and Applications

Electromagnetic energy harvestings and hybridized EMEHs have both attracted the attention of researchers for human-based energy harvesting. This section describes the recent configurations and designs of both technologies for wearable and self-powered applications.

3.2.1 Self-Powered Wristwatch

As the human body exhibits large amplitude movements at low frequencies, designing an energy harvester that can couple low frequency motion into transducer elements is a challenging task. Designers have proposed several designs to overcome such a challenge, with frequency up-conversion being one of the mainstream approaches. Halim et al. [125] designed a miniaturized electromagnetic energy harvester and integrated the harvester in a wristwatch so as to scavenge energy from hand motion, as shown in Fig. 15.

The design included magnetic flux stacks, which increased the power density without increasing the magnetic volume of the device. However, several authors have proposed different designs for smart wrist wearables [126, 127], but the problems in all devices were the lack of a miniaturized device to integrate in wearable electronics.

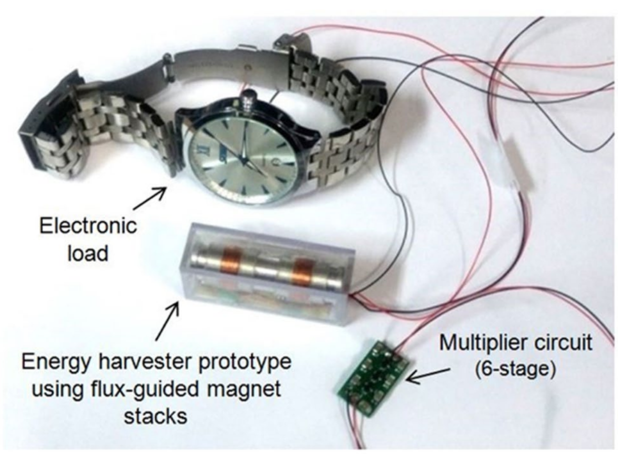

Fig. 15 Electromagnetic energy harvester integrated into wearable wristwatch [125]

Therefore, in order to address this problem, Wang et al. [21] fabricated a hybridized electromagnetic energy harvester by combining electromagnetic and triboelectric mechanisms by harvesting energy from human hand motion and integrated it in a self-powered wristwatch as shown in Fig. 16. Figure 16a shows a photograph of the hybridized EMEH and Fig. 16b shows the integration of the hybridized EMEH in a smart watch.

3.2.2 Smart Shoes

Traditionally, energy harvesters are placed in the shoe sole to scavenge human motion energy. However, due to the limited space inside the shoe, Wu et al. [128] proposed the electromagnetic energy harvester composed of permanent magnets attached with elastic strings that worked as a 3-degree-of-freedom (3-DoF) resonator to attach to the outer portion of the shoe. The 3-DoF resonator increased the bandwidth and energy conversion efficiency of the device. In addition, the energy storage circuit was used to store the extracted energy as shown in Fig. 17.

However, such types of designs make shoes more unfashionable and reduce the comfort level. Therefore, Liu et al. [123] fabricated self-powered shoes using an energy-based cell. The device, composed of EMEH and TEEH packaged together in a box, was embedded on a shoe sole as shown in Fig. 18.

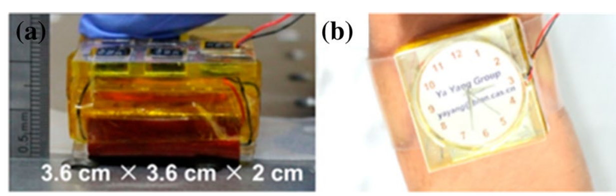

Fig. 16 Smart watch **a** photograph of hybridized electromagnetic energy harvester, **b** self-powered wearable wristwatch [21]

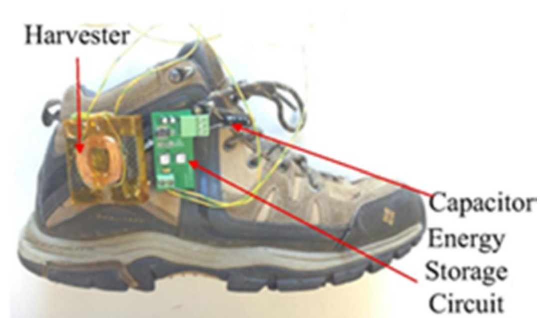

Fig. 17 Smart shoe using EMEH [128]

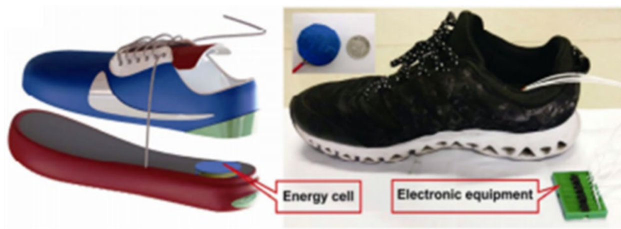

Fig. 18 Smart shoes using hybridized EMEH [123]

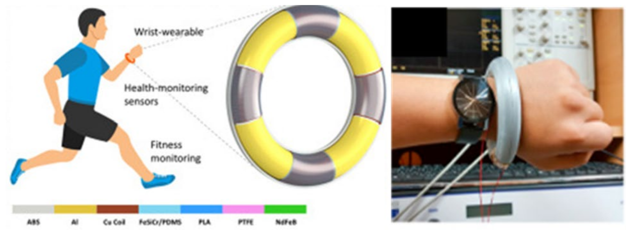

Fig. 20 Hybrid EMEH-TENG for biomedical monitoring and self-powered wearable devices [129]

3.2.3 Biomedical Monitoring

Electromagnetic energy harvestings have also been used in the biomedical industry for health monitoring. Anjum et al. [116] proposed a broadband electromagnetic energy harvester design targeted for biomedical applications such as health monitors and pulse oximeters for exercising persons with higher outputs and broader bandwidths, as shown in Fig. 19. In Fig. 19a, the device is attached on the arm of a walking person in the first experiment for data acquisition. Figure 19b shows the second experiment for data acquisition for a running person.

Still, EMEHs faces a large drawback, and that is human comfort. In order to address this issue, Maharjan et al. [129] presented a flexible wearable hybridized electromagnetic-triboelectric energy harvester for powering a health and fitness monitoring system by scavenging energy from hand motion. The flux concentrator is used around the copper coil to enhance the power output. The design demonstrated high-efficiency performance and ease for integration into wearable devices such as a wristwatch, as shown in Fig. 20.

3.3 Challenges and Issues

Usually, EMEHs are resonant based devices, and in order to obtain maximum power output they must perform at their resonant frequencies [130]. By contrast, human motion falls in an ultra-low frequency range and exhibits high amplitude vibrations, making them unsuitable for human motion-based energy harvesting. In order to resolve this problem, designers have used a springless structure for low-frequency oscillators. Secondly, for spring-mass-damper systems, most researchers have proposed a frequency up-conversion technique [110, 115] to maximize power output. Berdy et al. [131] used a magnetic levitation vibration energy harvester to overcome this issue. Fan et al. tuned the operating frequency band using a monostable EMEH that could shift the bandwidth to the low-frequency range [132]. Frequency up-conversion techniques have widely opted in literature for wearable energy harvesting from human motion [133, 134]. However, the internal travel range of such energy harvesters is limited which in turn, restricts power generation. Halim et al. [126] reported modeling and analysis of wearable rotational energy harvester with the ability to predict the electromechanical behavior and power output from the different human body locations (chest, wrist, ankle, and waist) and further developed an electromagnetic energy harvester prototype to verify the model forecasts. Another issue in EMEHs is low flexibility, as human motion involves complex motion that requires flexible wearable devices to wear. Zhang et al. [117] used microfabricated flexible coils to solve this problem.

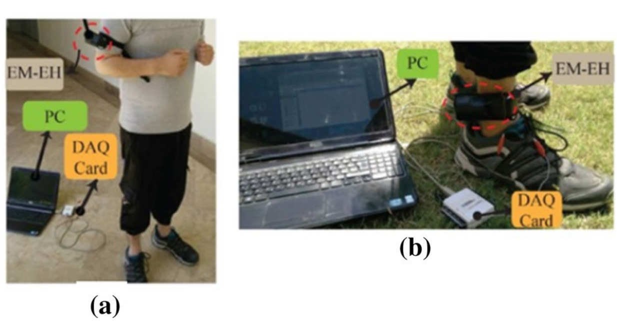

Fig. 19 EMEH biomedical application. **a** Data collection in walking position. **b** Data collection in running position [116]

One big challenge in EMEH is that it is complex to miniaturize and difficult to integrate with wearable energy harvesters. Usually, EMEH suffers from high weight and large size, which makes them highly unsuitable for wearable devices. Some authors cope with this issue by changing the location of the harvester to high surface area locations of wearables to integrate. For example, Ylli et al. [114] employed EMEH on the outside portion of the shoe because it was impossible to integrate inside the shoe sole due to the bigger size of EMEH. Some designers have sacrificed power output at the cost of less space by decreasing the number of coils in the device [116]. Many researchers have hybridized EMEH with TEEH in order to minimize the miniaturizing issue and maximize the power outputs for self-powered wearable devices [135] and biomedical applications [129]. Currently, EMEHs are not suitable for smart wearable electronics; however, by solving the large size issue, these devices depict the potential to efficiently harvest energy from human motion. In the future, hybridization of EMEHs with other mechanisms may help in solving the device efficiency challenge in a compact configuration.

4 Triboelectric Energy Harvesting by Using Human Motion

Recently, human-based triboelectric energy harvesting has gained much importance because of its associated high power density, low operating frequency, and high conversion efficiency [22, 105]. This section discusses the working principle of triboelectric energy harvesters along with recent design configurations and challenges.

4.1 Working Principle of Triboelectric Nano Generator Energy Harvesting

Triboelectric energy harvesters (TEEHs) work on a well-known phenomenon called triboelectrification [136]. Generally, the working principle of TEEHs is explained as, when two materials with dissimilar polarities make contact with each other, charge transfer takes place due to the triboelectric effect, resulting in the creation of opposite charges on each side of the surface. If these materials connect with metal electrodes at the two non-contacting ends, the detachment of surfaces leads to charge accumulation because of the electrostatic induction effect. Repeating contact between the two surfaces results in charge flow in opposite ends. Mathematically, if the charge accumulation on the surfaces is Q_f, then the initial voltage V_{tr} between the two electrodes is given in Eq. (10).

$$V_{tr} = -\frac{Q_f d_{tr}}{\varepsilon_0 S_{tr}} \tag{10}$$

where d_{tr} is the interlayer distance, S_{tr} is the surface area of the metal electrode, and ε_0 denotes the vacuum permittivity. Equation (11) shows the induced current I_{tr} in the external electrodes.

$$I_{tr} = C_{tr}\frac{\partial V_{tr}}{\partial t} + V_{tr}\frac{\partial C_{tr}}{\partial t} \tag{11}$$

where C_{tr} represents the capacitance of the given system. TEEH is further classified into four different working modes [137], as discussed comprehensively in the following subsections.

Table 2 shows the list of materials with the tendency to gain positive or negative charges upon contact electrification, and this list is often known as the triboelectric series. Human skin exhibits the highest affinity to lose the electron in the list. Due to this fact, the triboelectricity has gained much interest from the researchers and plenty of work has been done on triboelectric energy harvesting by using human motion.

Table 2 Triboelectric series [138]

Tend to loose electron (+)	Human skin
↑	Glass
	Nylon
	Fabrics
	Metals
	Polyester
	Polyethylene
	Polyimide
↓	Polyvinyl chloride
Tend to gain electron(-)	Fluoropolymer

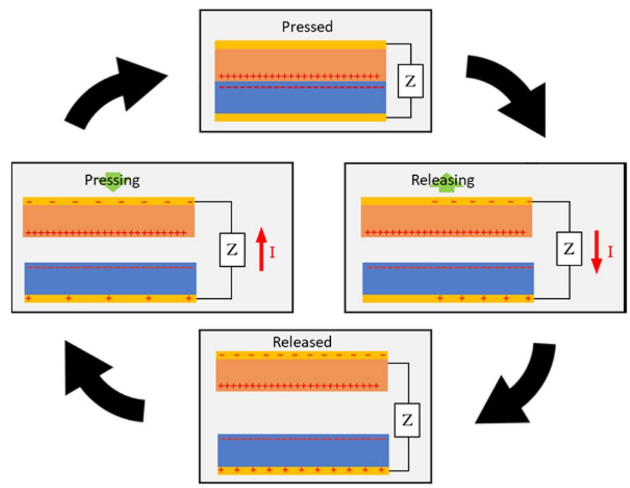

Fig. 21 Working principle of VCSM [140]

4.1.1 Vertical Contact-Separation Mode (VCSM)

Vertical contact-separation mode was the first designed operational form of the TEEHs [23, 139]. It works on the principle of cyclic contact and separation between the two surfaces in order to provide an output electric current, as shown in Fig. 21.

Various researchers have suggested different designs for the VCSM. Bai et al. [141] designed a zigzag-shaped multilayered triboelectric energy harvester (TEEH) and integrated into clothes by joining five layers of assemblies in parallel on a substrate, where each assembly was composed of an aluminum foil and polytetrafluoroethylene (PTFE) thin film, and generated a peak OCV of 215 V and short circuit voltage (SCV) of 0.66 mA. Figure 22 shows the working mechanism of the multilayered triboelectric energy harvester. Figure 22a shows the original position of the plates with an angle θ_1. An external force brings the two films in contact with each other,

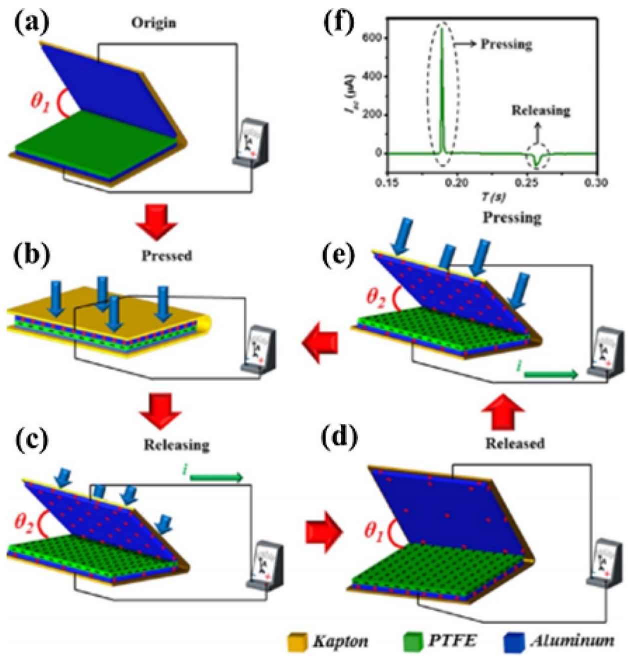

Fig. 22 Schematic diagram of multilayered Triboelectric energy harvester based on VCSM. **a** Original position of plates, **b** pressing of plates by applying force, **c** withdrawal of force, **d** revert to original position, **e** reapplying of force, **f** short-circuit current during one cycle [141]

resulting in the formation of positive and negative charges on Aluminum and PTFE films, as shown in Fig. 22b. Upon the removal of the compressive force, the two plates started to separate with angle θ_2 as shown in Fig. 22c. The electric potential allows for the electrons to flow from end electrodes to contact electrodes, eliminating triboelectric (TE) charges and leaving behind inductive charges. Figure 22d exhibits the plates returning to the starting position with TE charges substantially eliminated from contact electrodes. Reapplying the pressure on the upper plate drives the electric flow from the back electrode and diminishes the positive induction charges as shown in Fig. 22e. Figure 22f represents the SCV of the triboelectric energy harvester throughout one cycle. Similarly, Zhu et al. [142] proposed a multilayered triboelectric energy harvester of insole application and generated 220 V and 600 µA during walking. Wang et al. [23] designed a curved-shaped triboelectric energy harvester by employing the triboelectric effect between a polymer and small metal film and generated an energy volume density, a current density, and an output voltage of 128 mW/cm^3, 15.5 µA/cm^2, and 230 V, respectively. Yang et al. [143] fabricated a rhombic-shaped triboelectric energy harvester to scavenge energy from human walking motion by combining contact-separation and a sliding electrification mechanism and observed the power density of 30.7 W/m^2. Hou et al. [144] reported a TEEH prototype for a human shoe insole

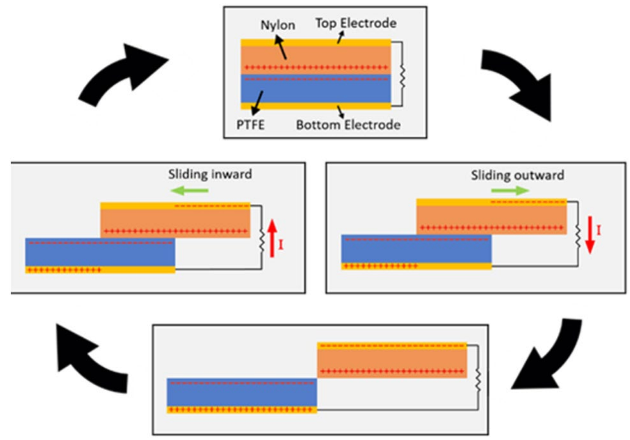

Fig. 23 Schematics of working mechanism of in-plane sliding mode [24]

based on VCSM and achieved a voltage of 220 V and a current density of 40 mA during walking. Further literature regarding VCSM can be found in these references [145, 146].

4.1.2 In-Plane Sliding Mode (IPSM)

The in-plane sliding mechanism is usually preferred over VCSM because of its ease to integrate in wearable devices and ability to generate more electricity [147]. In general, this mechanism is usually used for planar motion, disc rotation, or cylindrical rotation [148, 149]. Wang et al. [24] proposed a triboelectric harvester based on IPSM for the first time by using the relative sliding motion between the two surfaces (nylon and PTFE film). Figure 23 illustrates the working mechanism of the in-plane sliding mode. From the start, the two surfaces (PTFE film and nylon) overlap with each other to form full contact. Due to the triboelectrification, positive charges appeared on the nylon surface, and PTFE film acquired negative charges. When the top surface started to slide outwards, a charge separation occurred due to the reduction in the contact area of surfaces. The charge separation resulted in the formation of the electric field, creating a higher potential at the top electrode, and the current starts to flow from the top to bottom electrodes. This process continues until the two surfaces had fully slid across each other. Similarly, when the top surface began to move inwards, the separated charges started to make contact with each other due to the increase in contact surface area and the current flows from the bottom to top electrodes until these two surfaces entirely overlapped each other. Finally, the device returns to an original position, leaving behind no charges on the electrodes. The output current depends on the rate of two surfaces sliding across each other. The designed harvester showed a higher efficiency with a peak OCV of 1300 V and short circuit current density of 4.1 mA/m^2.

Researchers have proposed different design configurations for the in-plane sliding mode. Song et al. [150] fabricated a smart bracelet by harvesting energy from human motion using the in-plane sliding method, and obtained a maximum power output of 300.4 μW and conversion efficiency of 69.3%. Wang et al. [151] proposed textile-based triboelectric energy harvesters based on the swing motion of arms. The harvester utilized the friction between the fabrics of the underneath arm and sleeve working as two pairs of sliding mode (as shown in Fig. 24), and generated a peak power output of 7 mW. Shao et al. [152] developed a theoretical formulation for the in-plane sliding mode by considering the effect of external forces, and compared the theoretical model with experimental results. Zhu et al. [153] designed a micro grating thin film-based triboelectric energy harvester. The device worked on the in-plane sliding motion of arrays of micro-gratings, ultimately producing a power output of 3 W with a conversion efficiency of 50%. Similarly, various authors have used the in-plane sliding mode to harness energy for self-powered electronics [154].

4.1.3 Single Electrode Mode

The single electrode mode usually consists of a grounded electrode, movable active element, and friction layer. Wang et al. [155] demonstrated the working mechanism of single electrode mode for triboelectric energy harvesting, shown in Fig. 25. Initially, the active member was in contact with the electrode through the friction layer. Due to the triboelectric effect, a positive charge appeared on the active element, while the friction layer acquired a negative charge. As the active layer separated from the friction layer, the electrode layer gained a positive charge due to the electrostatic induction effect. Thus, creating the potential difference between the ground and the electrode results in the flow of current from the electrode to ground. Once the active layer reached a far distance, electrical equilibrium formed between the electrode and friction layer, thus stopping the flow of electric current. Likewise, when the active layer moved back to the friction layer, the electric potential induced between the ground and electrode followed by the electrons moving in the opposite direction from ground to the electrode. Hence, the cyclic contact and separation between the ground and active member resulted in charge flow across the external circuit.

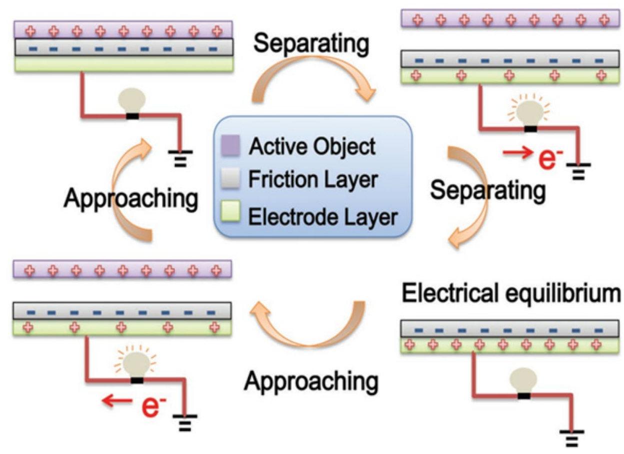

Fig. 25 Working mechanism of single electrode mode [155]

Several authors have proposed different working designs for single electrode mode for wearable devices that work by harvesting energy from human motion. Cheng et al [156]. used the human body as a natural electrode and a layer of ethylene–vinyl acetate copolymer pasted on the shoe sole that served as a friction layer between foot and marble ground in order to generate electricity from human walking, as demonstrated in Fig. 26, and observed the maximum

Fig. 24 Power textile based on in-plane sliding mode [151]

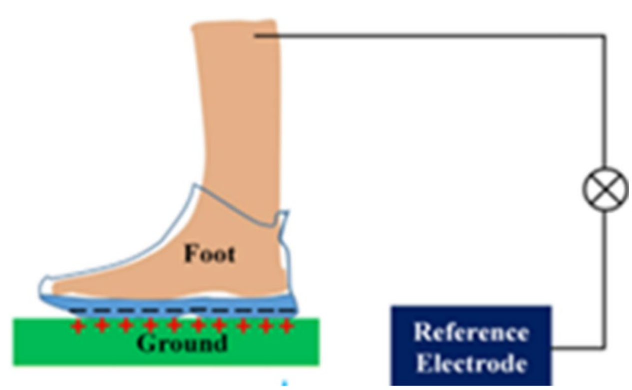

Fig. 26 Single electrode mode based energy harvesting from human walking [156]

output voltage of 810 V. Similarly, Zhang et al. [157] designed a triboelectric energy harvester based on a single electrode to integrate in human clothes for self-powered glucose biosensor. The design configuration used aluminum foil as an active layer, while polydimethylsiloxane (PDMS) and copper film were used as a friction and single electrode, respectively, and generated a maximum voltage of 17 V and current density of 0.02 μA/cm^2. Yang et al. [140] reported that a human skin-based triboelectric energy harvester utilizing the contact/separation between human skin and PDMS film recorded an OCV of 1000 V and current density of 8 mA/m^2. Fang et al. [158] developed a single electrode mode harvester that consisted of a layer of elastic rubber and aluminum foil served as the electrode for self-powered sensors. Similarly, multiple researchers have reported different designs for single electrode mode energy harvesters [159–161].

4.1.4 Freestanding Triboelectric-Layer Mode

The freestanding electrode mode possesses unique characteristics for harvesting energy from a freely moving human energy source with enhanced power outputs. Wang et al. [26] first developed this triboelectric mode of harvesting. This harvester is composed of a freely moving triboelectric layer with two stationary metal electrodes, as shown in Fig. 27. The triboelectric layer can slide back and forth over the two electrodes on the same plane, generating an alternating electric current because of the electrostatic induction effect.

Various authors have suggested different designs for freestanding electrode mode by scavenging energy from human motion for powering self-powered and wearable electronics. Similarly, a lot of work has been performed in this field, such as that by Xie et al [162]. proposing a freestanding triboelectric harvester using a grating segmented-structured fluorinated ethylene propylene (FEP) triboelectric layer, two interdigital-fixed aluminum electrodes, and grating structured acrylic sheet as a substrate, as shown in Fig. 28. The designed device used human hand motion as an energy source and harvested approximately 135 V of voltage, 9 mA/m^2 of current density, and 1.2 W/m^2 of maximum density. Guo et al. [163] fabricated an ultra-robust rotational mechanical energy harvester based on freestanding electrode mode with a power capacity of 260 mW/m^2. Further literature regarding freestanding electrode mode can be found in these references [164, 165].

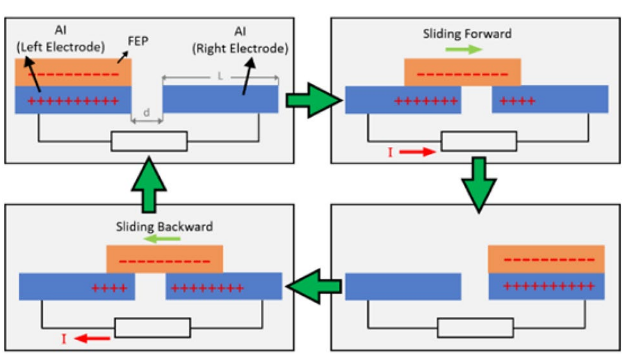

Fig. 27 Working mechanism of freestanding triboelectric harvester [26]

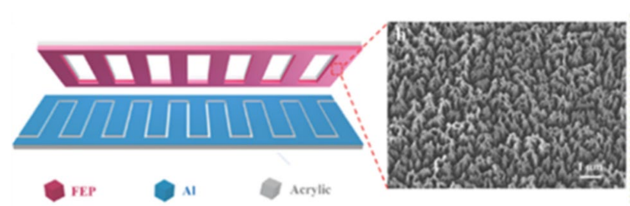

Fig. 28 Structure of freestanding triboelectric energy harvester [162]

4.2 Recent Progress and Applications in Triboelectric Energy Harvesting

Triboelectric energy harvesting is an advanced technique compared to piezoelectric and electromagnetic energy harvesting, because of its easy fabrication at the nanoscale size and low operation frequency [154]. Triboelectric energy harvesting is quite famous for harnessing energy from human in vitro and in vivo motion. This section describes the most recent design configurations of TEEHs for wearable and self-powered applications.

4.2.1 Smart Textile

Lately, smart textiles with the ability to harvest energy from human motion have attracted much attention due to their versatile applications [166–168]. However, there are many issues related to this area, such as biological compatibility, stretchability, and durability. Hence, various authors have attempted to solve these challenges in smart textiles. Tian et al. [169] reported a highly flexible double-layer stacked triboelectric textile composed of conductive textile and silicone rubber efficient active element. This device can harvest energy from human motion by integrating movement of different parts of the body, as shown in Fig. 29a. In addition to energy harvesting, this device can also work in human motion monitoring, as shown in Fig. 29b. Figure 29c shows the ability of this textile-based energy harvester for powering portable electronics. Xiong et al. [170] fabricated a durable, biocompatible, and washable textile that can extract energy from human skin in order to drive portable and self-powered electronics. Furthermore, Kwak et al. [171] designed a stretchable textile-based triboelectric energy harvester for human motion energy harvesting by using knitted fabrics.

Fig. 29 Demonstration of different applications of double layer stacked triboelectric energy harvesting textile. **a** Attach at different parts of human body, **b** smart sensor, **c** powering portable electronics [169]

Aside from that, Seung [172] fabricated a foldable nano patterned textile-based energy harvester by solving the stretchability and flexibility issues. Likewise, various authors have fabricated biocompatible, flexible, and washable smart textiles in these references [173, 174].

4.2.2 Smart Wearable

Energy harvesting using triboelectric energy harvesters as wearable devices has earned immense importance because of the drawbacks of other harvesting technologies. PEEHs face the issues of poor coupling at the microscale [175] and self-discharging [176]. EMEHs have low efficiency [177] and are complex to fabricate at the nanoscale [176]. By contrast, triboelectric energy harvesters are much more suitable to integrate in wearable devices because of their easy fabrication at nanoscale. In the literature, TEEHs are integrated into various wearable devices such as footwear for powering self-powered electronics. However, wearable devices based on TEEHs have also been shown to suffer from various issues like biocompatibility, humidity, and flexibility. Shen et al. [178] presented a humidity resisting TEEH that can harvest energy from human motion like hand tapping and walking that can generate enough electricity to power a calculator, thermal meter, smart watch, and multiple LEDs in varying humidity levels. Li et al [179] fabricated a flexible multilayer elastomeric structure TEEH and integrated it in a shoe so as to harvest energy from human walking with the ability to record exercise and fitness data through a multipedometer and fitness tracker, as shown in Fig. 30. Figure 30a shows multilayer TEEH and Fig. 30b shows a photo of smart shoes with pedometer and fitness tracker functions. Figure 30c, d show the pedometer and fitness tracker powered by TEEH by harnessing energy from walking. Similarly, Zhu et al. [180] proposed a flexible TEEH, consisting of a dual layer of active elements of polydimethylsiloxane and multiwall carbon nanotube that can be attached to a human shoe for scavenging energy from human walking. Furthermore, Hou et al. [144] designed a robust, low-cost, and high performance TEEH-based shoe insole for harvesting energy from human walking.

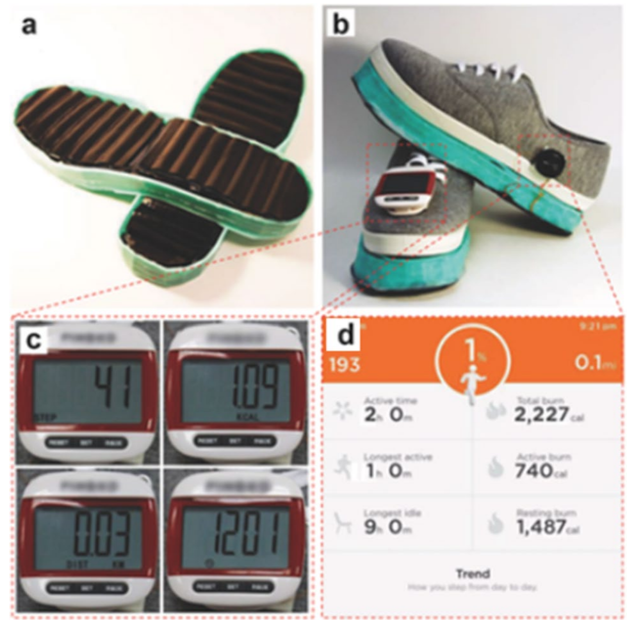

Fig. 30 Smart shoes **a** shoe outsoles composed of multilayer TEEH, **b** smart shoe with pedometer and fitness tracker functions, **c** pedometer, **d** fitness tracker [179]

4.2.3 Smart Skin

Electronic skin (e-skin) is generally defined as an array of sensors and actuators that can perceive the thermal and mechanical stimuli with human-like sensory abilities. In order to exhibit the characteristics of human skin, e-skin must withstand prolonged and repeated mechanical stimuli such as strain, pressure, and flexion. Electronic skin is a self-powered sensor that does not require the presence of external power sources such as batteries. Smart skin-based

TEEH can perform as both a sensor and mechanical energy harvester [181]. The integration of TEEH with e-skin has brought about a lot of applications in touch-based sensors [140], human–machine interfaces [182], and artificial intelligence systems [183]. TEEH output performance dramatically relies on the quantity and frequency of external stimuli. Yang et al. [140] proposed human skin like TEEH that can be used as a self-powered tactile sensor for touchpad technology (cell phone and keyboard) and harness energy from human hand and fingers touch pressure. Dhakar et al. [184] fabricated a novel stretchable and wearable self-powered motion sensor that can identify human finger movement for static and dynamic states and provides the location and pressure of the human touch. Wang et al. [185] reported a transparent skin like TEEH using polydimethylsiloxane as an active element and polyconic as an electrode, and harvested energies from human motions such as tapping, bending, and curling for self-powered systems. Similarly, Lai et al. [186] designed a highly stretchable and washable textile-based TEEH that exhibits both active tactile sensing and biomechanical harvesting properties during contact with human skin. Figure 31 shows the textile-based harvester, worn on a human wrist that produces electricity when touching human skin so as to power the self-powered smart watch. Jiang et al. [187] fabricated a compact self-powered skin-based TEEH combined with micro-supercapacitors for both energy harvesting and storage.

4.2.4 Biomedical Health Monitoring

Recently, triboelectric energy harvesters have shown considerable potential in the field of biomedical applications for harvesting energy from human in vitro motion as well as from human in vivo motion such as pulse vibration, respiration, and heartbeat. Generally, biomedical devices operate on small energy, and the energy harvested from human motion is enough to run these devices [188, 189]. Ding et al. [190] developed a self-powered tactile sensor composed of carbon nanotubes doped with TEEH with excellent features such as durability, high sensitivity, and quick response. Further, the device was used in the design of a sleep belt for real-time heart rate and breath monitoring, showing its potential for disease diagnosis as presented in Fig. 32. Figure 32a shows the design of the carbon nanotube doped TEEH. The belt is attached under the chest of the subject to monitor heart rate and breathing, as shown in Fig. 32b. Figure 32c shows the calculation setup to monitor heartbeat and breathing, and the ballistocardiogram output voltage of a sleeping person is shown in Fig. 32d. Ma et al. [191] reported a self-powered multifunctional triboelectric sensor that provides precise, regular, and real-time monitoring for various physiological and pathological changings in the human body. Lin et al. [12] constructed a self-powered body sensor network for human heart rate monitoring by harvesting energy from human walking. The proposed device used Bluetooth to connect with a mobile, and instantly provides heart rate monitoring data on the mobile screen.

4.3 Issues and Challenges

Triboelectric energy harvesting is one of the most advanced harvesting technologies among all energy harvesting technologies. Although there have been many published papers in this field for different self-powered applications, this field still faces a number of problems and issues for biomechanical energy harvesting. Based on the working mechanism of TEEH, it is observed that to accomplish the useful triboelectrification, TEEH has to undergo long term and frequent mechanical impacts that result in device failure and series of problems such as safety hazards, loss of life span, and degradation of output performance [192]. Further, environmental dust and

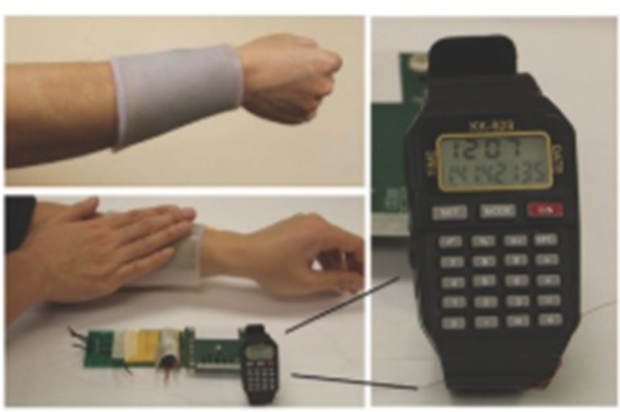

Fig. 31 Skin based energy harvesting for self-powering smart watch [186]

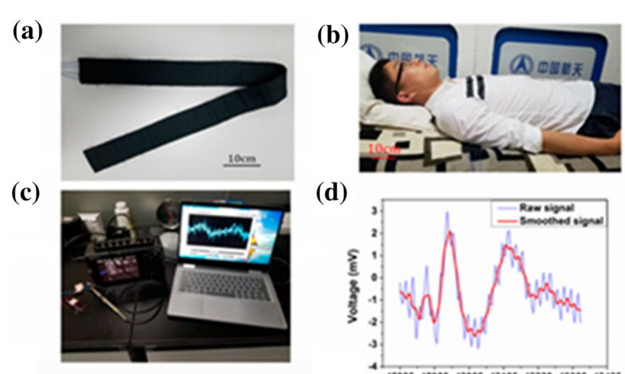

Fig. 32 Heartbeat and breath monitoring system **a** monitoring belt, **b** subject sleeping while wearing monitoring belt, **c** computational system, **d** ballistocardiogram for breath and heartbeat [190]

moisture decrease the output performance by penetrating the surface of TEEH thus compromising the reliability, robustness, and durability of these devices [193]. Therefore, it is essential to develop strategies to enhance the safety and sustainability of TEEHs. During the past few years, significant research has been done to overcome such issues. Xu et al. [194] recently reported self-healing TEEH by introducing a healable polymer into the device and recorded the recovery percentage in strain can reach up to 97% after healing the broken specimens for 2 h at 65 °C. Zheng et al. [195] presented multilayered encapsulation of TEEH to improve the durability and reliability in various severe environments. Moreover, liquid–solid contact TEEH is introduced to reduce the triboelectric material abrasion by frictional contact between the surfaces. The other advantage of such devices is their insensitivity to humidity which further improves their durability [196].

The other critical problem in TEEHs is the inflexibility of wearable harvesters due to their usage of metal electrodes. In order to overcome this problem, several researchers have proposed various designs. Lim et al. [197] constructed a fully stretchable harvester by using gold (Au) nano-sheets inserted between elastomers and electrodes that showed good properties in stretching and compression. He et al. [198] fabricated a highly stretchable harvester consisting of the fiber-convolving fiber and stretchable electrode. Similarly, different stretchable devices have been proposed, as given in these references [199, 200]. The other big problem is the humidity dependence of TEEHs. In order to tackle this problem, Chen et al. [201] reported a waterproof device using micro-patterned polydimethylsiloxane (PDMS) that behaved as a friction and covering layer due to its hydrophobic attribute. Likewise, Yan et al. [202] designed a triboelectric harvester with hydrophobic modifications that make the device capable for use under high humidity. Moreover, for the fabrication of fashionable garments, washability is the crucial factor. Yu et al. [203] designed a comfortable and fashionable textile made of core–shell yarn with natural fibers wrapped around conductive fibers. Similarly, Zhao et al. [173] solved this issue using loom weaving metallic yarns made from traditional weaving process. Skin-like and biocompatibility in human-based energy harvesting is substantially important, as these harvesters are in direct contact with human skin. Li et al. [204] used polypropylene ferroelectret in TEEH as a skin friendly material to overcome the biocompatibility issue. Further literature regarding issues and challenges for human powered triboelectric energy harvesters can be found in this Ref. [205]. Triboelectric energy harvesters are the most suitable energy harvesters among all, but they are still not fully developed for human motion energy harvesting due to the biocompatibility and flexibility issues.

TEEHs has shown considerable progress during the last few years. This technology can be revolutionary, but so far the future directions of this technology mainly depend on the issues and challenges that are still not addressed thoroughly. These issues and problems are summarized below:

1. Understanding the fundamental phenomenon of the working mechanism of TEEH is not yet clearly understood. So clearly understanding this phenomenon is very crucial as it forms the theoretical foundation of this technology.
2. Improving durability and reliability is a critical issue for further advancement in this technology.
3. The power management approach is much needed to overcome the high open circuit voltage and low output current issue to reduce power loss.

5 Comparison of Different Energy Harvesting Technologies

This section summarizes a detailed comparison of biomechanical energy harvesting technologies (piezoelectric, electromagnetic and triboelectric) and also present a brief overlook of other energy harvesting mechanisms opted for energy harvesting from human motion such as electrostatic, thermoelectric and pyroelectric energy harvesting.

Table 3 summarizes a brief comparison between different energy harvesting devices with displayed advantages, disadvantages, and challenges. Piezoelectric devices possess high voltage with little mechanical damping, but they are not compatible with the current miniaturized fabrication techniques. Electromagnetic devices, on the other hand, require no outside sources but usually experience coil losses and low output voltages. Due to enough power requirement, speed growth gears are usually added to meet desirable rotating velocity. Therefore, it is challenging to fabricate these devices at microscale level suitable for human body applications. Triboelectric harvesters show considerable advantages as compared to other abovementioned devices such as high power density, high conversion, and device flexibility. However, they have reliability and durability issues, and still, their working mechanism is not fully understood yet. The main challenges are to overcome washability, humidity, durability, and biocompatibility issues in these devices.

Table 4 summarizes the brief comparison of the ideal body parts and techniques used in the literature to effectively harvest energy from different harvesting technologies.

Table 3 Summary of Energy harvesting technologies in terms of their advantages, disadvantages and challenges

Type of energy harvesting	Advantages	Disadvantages	Challenges
PEEH	High energy density	Difficult integration [175]	Ultralow frequency of human [92]
	High voltage output [175]	Poor coupling [175]	Brittleness and rigidity of Piezo materials [206]
	No need of mechanical stopper [175]	High impedance and low current [207]	Complex human motion [7]
	High capacitance [208]	Need of piezoelectric material [177]	Toxicity of piezo materials [98]
	Small mechanical damping	Self-discharge at low frequency [176]	
	No voltage source [175]		
EMEH	No voltage source [175]	Low efficiency at low frequency [208]	Designing a flexible system [117]
	High output current [208]	Coil losses [177]	Difficulties in integration [114]
	Low output impedance [207]	Difficult integration [209]	Difficulties in miniaturizing [135]
	Small mechanical damping [175]	Low voltage [209]	
	No need of contacts [209]	Complicated to miniaturized [176]	
	Robust and durable [208]		
TEEH	Low operation frequency [105]	Mechanism not fully understood [22]	Inflexibility of electrode [197, 198]
	Device flexibility [105]	Difficult to integrate [22]	Humidity [202]
	High power density [22]	Low current at high voltage [105]	Washability [203]
	High conversion efficiency [22]	Durability [192]	Biocompatibility [173, 204]

Table 4 Summary of the techniques and the ideal body parts and movements for effectively harvesting energy

Type of energy harvesting	Ideal body parts and movements for energy harvesting	Techniques for harvesting energy effectively
Piezoelectric energy harvesting	Feet motion [74, 210] Arm and leg motion [211] Finger and palm motion [65]	Non linearity [76, 77] Double pendulum system [211] Frequency up conversion [93] Circuit management [212, 213]
Electromagnetic energy harvesting	Wrist motion [125] Feet motion [128] Knee motion [214] Leg and arm [132] Center of gravity of upper body [215]	Sprung eccentric rotor [118] Frequency up conversion [132] Spring clockwork mechanism [216] Spring-less system [217] Non linearity [218]
Triboelectric energy harvesting	Human Skin [170, 185] Hand tapping [178] Cloth [219] Cardiac and lung contraction and relaxation [190]	Ultrathin flexible single-electrode [155] Core–shell structure mechanism [203] Air-cushion mechanism [220] Liquid metal electrode [221]

Piezoelectric technology is researched mainly for muscle and knee motion, walking and palm grasping and implemented in the backpack, shoe and wrist devices. However, there is a need to enhance the performance and capture ultra-low frequency vibrations and human motion. Therefore, researchers used different techniques to overcome these challenges; among them, the frequency-up conversion is the most widely used technique. EMEHs are more suitable for utilizing the center of gravity movements of the upper body, lower limb movement, foot strike, and knee movements. However, to achieve the appropriate power output, it is necessary to amplify the human motion, for that gear train is usually used for portable rotary generators. Device efficiency of gear and generator type is much higher than other energy harvesting devices. Thus, for high power wearable energy harvesting, EMEHs are the best candidate due to their high power and high conversion efficiency. TEEHs are more practical and efficient for converting human body movements to electricity. The triboelectric harvester can also act as a body motion sensor that possesses the excellent potential for biomedical monitoring. Lately, self-powered electronic skin has attracted much attention. Due to the high response time and higher sensitivity, TEEH is a suitable candidate for self-powered electronic skin. However, TEEH suffers

Table 5 Summary of the performance of different energy harvesters exploiting human motion energy

Type of energy harvesting	Power output (mW)	Open circuit voltage (V)	Attached position
PEEH	28	20	Shoe [54]
	0.0002	0.7	Skin [50]
	45.6	–	Backpack strap [59]
	1.7–2	40–60	Arm and leg [211]
EMEH	0.5	0.24	Leg and arm [132]
	2.58	0.5	Arm [133]
	2.28	0.5	Shoe [128]
	0.203	1.12	Wrist watch [125]
	0.284	2.5	Hip mounted [222]
	1.7	1.4	Knee [214]
	32	–	Backpack [215]
TEEH	4.67	392	Skin [223]
	2.1	210	Shoe [224]
	–	1050	cloth [219]
	0.3	305	Wrist bracelet [150]

from low durability, biocompatibility, high power loss and inflexibility issues. Therefore, different techniques are used to overcome the abovementioned challenges and to harvest energy effectively as shown in Table 4.

Table 5 presents a brief comparison of the performance outputs of the different devices according to their attached position on the human body. TEEHs shows higher open circuit voltages up to several hundred of volts but for a very short period of time from several milliseconds to several hundred milliseconds during contact or release thus exhibiting higher instantaneous efficiency and low average energy conversion efficiency. However, these devices show better potential to integrate into wearable energy harvesting devices due to their easy scalability, light weight and flexibility. PEEHs also exhibits higher power outputs at higher frequency range however for a long frequency regimes such as human motion, their efficiency is low. However different studies [54] [59], enabled the operation frequency of PEEHs close to that of the human body and showed higher output performance which proves the practicability of these devices for human motion energy harvesting. On the other hand, EMEHs are more feasible for macroscale and mesoscale applications like knee cap, hip-mounted, and backpack applications and showed higher power outputs and higher energy conversion efficiency.

Among biomechanical energy harvesting technologies as reviewed above, electrostatic energy harvesters have also gained much interest due to their high output voltages and easy to integrate with microelectronics [225]. Electrostatic energy harvesters are capacitive devices; however, on the other hand, piezoelectric and electromagnetic harvesters are inductive. Electrostatic devices work through the relative displacement of two parallel plates with a layer of dielectric in between, thus allowing the conversion of mechanical motion into electrical energy. Usually, these devices are considered more suitable for low-frequency applications. The major limitation of these types of energy harvester is the need for the power source to charge the capacitors with the initial voltage to begin the energy harvesting process. And the other drawback is the complexity to fabricate these devices to maintain the minute gap between the two plates as the two plates should not come in contact with each other [226]. Furthermore, bandwidths and power density are the two important factors to evaluate the efficiency of such devices. Generally, optimal power outputs can only be obtained at narrow frequency ranges. ESEHs might be applicable to harvest energy for narrow bandwidths. However, larger bandwidths are required to harvest energy from human motion. To overcome these challenges, Lu et al. [227] developed a low frequency self-biased silicon-based electrostatic energy harvester with enhanced frequency bandwidths from 1 Hz to 60 Hz by using frequency up-conversion system. The prototype was tested with handshaking and obtained the maximum power density of 142 $\mu W/cm^3$. Further, various researchers have used these energy harvesters for biomechanical energy harvesting from human motion in these references [228, 229]. These devices are compatible with microfabrication techniques; however, the requirement of additional charge sources makes them least useful for human motion based energy harvesting.

Apart from biomechanical energy harvesting, the human body itself can generate heat for powering low powered devices. The use of mechanical energy harvesting technologies can be limited in health care systems and is not reliable for patients and older adults. Therefore in such cases, heat-based energy harvesters such as thermoelectric and pyroelectric devices are more favorable to use [230]. The main difference between these two energy harvesters is that thermoelectric energy harvester (TMEHs) depends on the space temperature difference across the device while pyroelectric energy harvesters (PREHs) relies on the temporal variation of the device temperature. Despite their long life, high reliability, and low maintenance benefits, these devices suffer from low energy conversion efficiency and high costs. Attempts are being made to overcome these challenges. These devices has plenty of applications in the human wearable and implantable biosensor. Ayesha et al. [231] and Kim et al. [232] recently built a self-powered pyroelectric and thermoelectric generator using body heat as an energy source for biomedical monitoring purposes such as respiration and heart monitoring with the maximum power density of 0.034 μW/cm^2 and 38 μW/cm^2. Further literature on such energy harvesters can be found in these references [233–235]. The capacity of these devices depends on the human body environment. However, due to the stable human body environment, the heat based devices is not satisfactory. Therefore making them less popular among heat conversion devices in future.

6 Conclusions

In this paper, we presented a comprehensive review of human motion-based energy harvesting for smart wearable electronics such as smart textiles, smart wrist wearables, smart footwear, smart skin, etc. We concentrated on biomechanical energy harvesting techniques and classified them according to their working principles. Further, various types of design configurations and prototypes for smart wearable electronics that can harvest energy from different biomechanical motions are reviewed and summarized in detail. Ultimately, challenges and issues for the development of self-powered wearable electronics are discussed under each harvesting technology section.

Harvesting biomechanical energy from human motion is quite a challenge, as it involves multidimensional movements such as the swinging motion of the arms, and exhibits low-frequency range (1–10 Hz). Therefore, several designs for smart wearable electronics using different energy harvesting technologies have been proposed to meet these challenges. Piezoelectric energy harvesters (PEHs) showed considerable potential for human motion-based energy harvesting. However, the operating bandwidths of piezoelectric devices are quite high, making them unfeasible for human motion-based energy harvesting. Moreover, linear PEHs are unable to scavenge energy from complex multidimensional movements of human motion.

By contrast, electromagnetic energy harvesters (EMEHs) showed a higher output power, but due to their lack of miniaturized designs, they are not suitable for smart wearable electronics. However, several designers have combined EMEHs with PEHs and Triboelectric energy harvesters (TEEHs) so as to build hybridized EMEHs, and improved their miniaturized designs for wearable devices. Triboelectric energy harvesters have emerged as the most advanced human motion-based energy harvesting technology. Among other techniques, TEEHs showed better performance regarding power outputs and integration in wearable devices. However, these harvesters suffer from issues of flexibility, stretchability, and humidity. Various designs have been proposed to solve these issues, but this technology still requires further improvement.

From the author's point of view, PEEHs and TEEHs are more likely to lighten up the future of human motion energy harvesting technology as recently, these devices have gained much improvement due to the progress in nanotechnology. However, the performance of PEEHs is not much improved, and the triboelectric phenomenon is still not fully understood yet; therefore it still lacks the theoretical foundation. Further, High open circuit voltage and low short circuit current results in power loss and therefore, power management approach is much needed in triboelectric energy harvesters. On the other hand, EMEHs are famous in macroscale and mesoscale applications owing to their higher energy outputs and higher conversion efficiency, but the major challenge is the miniaturization of EMEHs and compact configuration and therefore not suitable for wearable energy harvesting technology. Last, the most critical aspect is the gap between the frequency range of human motion and the operating frequency of the device for energy conversion efficiency. Hence, it is challenging to develop devices to harvest energy from the complex and irregular movements of the human. Hybridization of the different mechanisms might be an effective solution to scavenge energy from the human effectively. Further, the mutual interaction between different devices is not fully explored and understood yet. Last but not least, the development of low powered electronics may help in developing the energy harvesting devices as it will shorten down the gap between the output power of the harvester and the power demand of load electronics.

Although, currently, these biomechanical energy-harvesting technologies are not fully developed and suitable for smart wearable electronics, according to its rapid growth and progress, it can be forecasted that human motion-based energy harvesting will soon pave its path into the real world.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Fan, F. R., Tang, W., & Wang, Z. L. (2016). Flexible nanogenerators for energy harvesting and self-powered electronics. *Advanced Materials, 28*(22), 4283–4305. https://doi.org/10.1002/adma.201504299.
2. Song, P., Yang, G., Lang, T., & Yong, K.-T. (2018). Nanogenerators for wearable bioelectronics and biodevices. *Journal of Physics D: Applied Physics, 52*(2), 023002.
3. Wang, Hao, & Jasim, Abbas. (2018). Energy harvesting technologies in roadway and bridge for different applications—A

comprehensive review. *Applied Energy, 212,* 1083–1094. https://doi.org/10.1016/j.apenergy.2017.12.125.
4. Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering*. https://doi.org/10.1080/23311916.2016.1167990.
5. Xie, L., & Cai, M. (2014). Human motion: Sustainable power for wearable electronics. *IEEE Pervasive Computing, 13*(4), 42–49. https://doi.org/10.1109/MPRV.2014.67.
6. Roundy, S., & Trolier-McKinstry, S. (2018). Materials and approaches for on-body energy harvesting. *MRS Bulletin, 43*(3), 206–213.
7. Fan, K., Yu, B., Zhu, Y., Liu, Z., & Wang, L. (2017). Scavenging energy from the motion of human lower limbs via a piezoelectric energy harvester. *International Journal of Modern Physics B, 31*(07), 1741011. https://doi.org/10.1142/S0217979217410119.
8. Kim, M.-O., Pyo, S., Oh, Y., Kang, Y., Cho, K.-H., Choi, J., et al. (2018). Flexible and multi-directional piezoelectric energy harvester for self-powered human motion sensor. *Smart Materials and Structures, 27*(3), 035001. https://doi.org/10.1088/1361-665X/aaa722.
9. Leonov, V. (2011). Energy harvesting for self-powered wearable devices. In *Wearable monitoring systems* (pp. 27–49). Springer.
10. Kakihara, R., Kariya, K., Matsushita, Y., Yoshimura, T., & Fujimura, N. (2018). Investigation of piezoelectric energy harvesting from human walking. In *Journal of Physics: Conference Series* (Vol. 1052, p. 012113). IOP Publishing.
11. Saha, C. R., O'Donnell, T., Wang, N., & McCloskey, P. (2008). Electromagnetic generator for harvesting energy from human motion. *Sensors and Actuators A: Physical, 147*(1), 248–253. https://doi.org/10.1016/j.sna.2008.03.008.
12. Lin, Z., Chen, J., Li, X., Zhou, Z., Meng, K., Wei, W., et al. (2017). Triboelectric nanogenerator enabled body sensor network for self-powered human heart-rate monitoring. *ACS Nano, 11*(9), 8830–8837.
13. Kang, M.-G., Jung, W.-S., Kang, C.-Y., & Yoon, S.-J. (2016). Recent progress on PZT based piezoelectric energy harvesting technologies. *Actuators, 5*(1), 5. https://doi.org/10.3390/act5010005.
14. Narita, F., & Fox, M. (2018). A review on piezoelectric, magnetostrictive, and magnetoelectric materials and device technologies for energy harvesting applications. *Advanced Engineering Materials, 20*(5), 1700743. https://doi.org/10.1002/adem.201700743.
15. Wang, Z. L. (2018). Nanogenerators, self-powered systems, blue energy, piezotronics and piezo-phototronics—A recall on the original thoughts for coining these fields. *Nano Energy, 54,* 477–483.
16. Zhang, Y., Cao, J., Zhu, H., & Lei, Y. (2019). Design, modeling and experimental verification of circular Halbach electromagnetic energy harvesting from bearing motion. *Energy Conversion and Management, 180,* 811–821.
17. Dinulovic, D., Brooks, M., Haug, M., & Petrovic, T. (2015). Rotational electromagnetic energy harvesting system. *Physics Procedia, 75,* 1244–1251. https://doi.org/10.1016/j.phpro.2015.12.137.
18. Niroomand, M., & Foroughi, H. R. (2016). A rotary electromagnetic microgenerator for energy harvesting from human motions. *Journal of Applied Research and Technology, 14*(4), 259–267. https://doi.org/10.1016/j.jart.2016.06.002.
19. Halim, M. A., Rantz, R., Zhang, Q., Gu, L., Yang, K., & Roundy, S. (2017). Electromagnetic energy harvesting from swing-arm motion using rotational eccentric mass structure. In *2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems* (*TRANSDUCERS*) (pp. 1863–1866). Presented at the 2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), Kaohsiung, Taiwan: IEEE. https://doi.org/10.1109/transducers.2017.7994434.
20. Wu, Y., Qiu, J., Zhou, S., Ji, H., Chen, Y., & Li, S. (2018). A piezoelectric spring pendulum oscillator used for multi-directional and ultra-low frequency vibration energy harvesting. *Applied Energy, 231,* 600–614. https://doi.org/10.1016/j.apenergy.2018.09.082.
21. Quan, T., Wang, X., Wang, Z. L., & Yang, Y. (2015). Hybridized electromagnetic-triboelectric nanogenerator for a self-powered electronic watch. *ACS Nano, 9*(12), 12301–12310. https://doi.org/10.1021/acsnano.5b05598.
22. Wang, Z. L., Chen, J., & Lin, L. (2015). Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy and Environmental Science, 8*(8), 2250–2282.
23. Wang, S., Lin, L., & Wang, Z. L. (2012). Nanoscale triboelectric-effect-enabled energy conversion for sustainably powering portable electronics. *Nano Letters, 12*(12), 6339–6346. https://doi.org/10.1021/nl303573d.
24. Wang, S., Lin, L., Xie, Y., Jing, Q., Niu, S., & Wang, Z. L. (2013). Sliding-triboelectric nanogenerators based on in-plane charge-separation mechanism. *Nano Letters, 13*(5), 2226–2233. https://doi.org/10.1021/nl400738p.
25. Wang, X., Song, W.-Z., You, M.-H., Zhang, J., Yu, M., Fan, Z., et al. (2018). Bionic single-electrode electronic skin unit based on piezoelectric nanogenerator. *ACS Nano, 12*(8), 8588–8596. https://doi.org/10.1021/acsnano.8b04244.
26. Wang, S., Xie, Y., Niu, S., Lin, L., & Wang, Z. L. (2014). Freestanding triboelectric-layer-based nanogenerators for harvesting energy from a moving object or human motion in contact and non-contact modes. *Advanced Materials, 26*(18), 2818–2824.
27. Ha, M., Park, J., Lee, Y., & Ko, H. (2015). Triboelectric generators and sensors for self-powered wearable electronics. *ACS Nano, 9*(4), 3421–3427.
28. Khalifa, S., Lan, G., Hassan, M., Seneviratne, A., & Das, S. K. (2018). HARKE: Human activity recognition from kinetic energy harvesting data in wearable devices. *IEEE Transactions on Mobile Computing, 17*(6), 1353–1368. https://doi.org/10.1109/TMC.2017.2761744.
29. Dagdeviren, C., Li, Z., & Wang, Z. L. (2017). Energy harvesting from the animal/human body for self-powered electronics. *Annual Review of Biomedical Engineering, 19*(1), 85–108. https://doi.org/10.1146/annurev-bioeng-071516-044517.
30. Priya, S., Song, H.-C., Zhou, Y., Varghese, R., Chopra, A., Kim, S.-G., et al. (2017). A review on piezoelectric energy harvesting: Materials, methods, and circuits. *Energy Harvesting and Systems*. https://doi.org/10.1515/ehs-2016-0028.
31. Cui, J., Yoon, H., & Youn, B. D. (2018). An omnidirectional biomechanical energy harvesting (OBEH) sidewalk block for a Self-generative power grid in a smart city. *International Journal of Precision Engineering and Manufacturing-Green Technology, 5*(4), 507–517.
32. Elahi, H., Eugeni, M., & Gaudenzi, P. (2018). A review on mechanisms for piezoelectric-based energy harvesters. *Energies, 11*(7), 1850. https://doi.org/10.3390/en11071850.
33. Jaffe, B. (2012). *Piezoelectric ceramics*. Amsterdam: Elsevier.
34. Chopra, I. (2002). Review of state of art of smart structures and integrated systems. *AIAA Journal, 40*(11), 2145–2187.
35. Kim, H. S., Kim, J.-H., & Kim, J. (2011). A review of piezoelectric energy harvesting based on vibration. *International Journal of Precision Engineering and Manufacturing, 12*(6), 1129–1141. https://doi.org/10.1007/s12541-011-0151-3.
36. Stanton, S. C., McGehee, C. C., & Mann, B. P. (2010). Nonlinear dynamics for broadband energy harvesting: Investigation of a bistable piezoelectric inertial generator. *Physica D: Nonlinear*

Phenomena, 239(10), 640–653. https://doi.org/10.1016/j.physd.2010.01.019.
37. Ramlan, R., Brennan, M. J., Mace, B. R., & Kovacic, I. (2010). Potential benefits of a non-linear stiffness in an energy harvesting device. *Nonlinear Dynamics, 59*(4), 545–558. https://doi.org/10.1007/s11071-009-9561-5.
38. Neiss, S., Goldschmidtboeing, F., Kroener, M., & Woias, P. (2014). Analytical model for nonlinear piezoelectric energy harvesting devices. *Smart Materials and Structures, 23*(10), 105031. https://doi.org/10.1088/0964-1726/23/10/105031.
39. Daqaq, M. F., Masana, R., Erturk, A., & Dane Quinn, D. (2014). On the role of nonlinearities in vibratory energy harvesting: A critical review and discussion. *Applied Mechanics Reviews, 66*(4), 040801. https://doi.org/10.1115/1.4026278.
40. Krueger, H. H. A., & Berlincourt, D. (1961). Effects of high static stress on the piezoelectric properties of transducer materials. *The Journal of the Acoustical Society of America, 33*(10), 1339–1344.
41. Turkmen, A. C., & Celik, C. (2018). Energy harvesting with the piezoelectric material integrated shoe. *Energy, 150,* 556–564. https://doi.org/10.1016/j.energy.2017.12.159.
42. Song, J., Zhao, G., Li, B., & Wang, J. (2017). Design optimization of PVDF-based piezoelectric energy harvesters. *Heliyon, 3*(9), e00377. https://doi.org/10.1016/j.heliyon.2017.e00377.
43. Nguyen, C. H., Hanke, U., & Halvorsen, E. (2018). Actuation of piezoelectric layered beams with d_{31} and d_{33} coupling. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 65*(5), 815–827. https://doi.org/10.1109/TUFFC.2018.2808239.
44. Jenkins, K., Nguyen, V., Zhu, R., & Yang, R. (2015). Piezotronic effect: An emerging mechanism for sensing applications. *Sensors (Basel, Switzerland), 15*(9), 22914–22940. https://doi.org/10.3390/s150922914.
45. Li, L., Xu, J., Liu, J., & Gao, F. (2018). Recent progress on piezoelectric energy harvesting: Structures and materials. *Advanced Composites and Hybrid Materials, 1*(3), 478–505. https://doi.org/10.1007/s42114-018-0046-1.
46. Hao, J., Li, W., Zhai, J., & Chen, H. (2019). Progress in high-strain perovskite piezoelectric ceramics. *Materials Science and Engineering: R: Reports, 135,* 1–57. https://doi.org/10.1016/j.mser.2018.08.001.
47. Xu, X., Cao, D., Yang, H., & He, M. (2018). Application of piezoelectric transducer in energy harvesting in pavement. *International Journal of Pavement Research and Technology, 11*(4), 388–395. https://doi.org/10.1016/j.ijprt.2017.09.011.
48. Lee, A. J., Wang, Y., & Inman, D. J. (2013). Energy harvesting of piezoelectric stack actuator from a shock event. *Journal of Vibration and Acoustics, 136*(1), 011016. https://doi.org/10.1115/1.4025878.
49. Feenstra, J., Granstrom, J., & Sodano, H. (2008). Energy harvesting through a backpack employing a mechanically amplified piezoelectric stack. *Mechanical Systems and Signal Processing, 22*(3), 721–734. https://doi.org/10.1016/j.ymssp.2007.09.015.
50. Guido, F., Qualtieri, A., Algieri, L., Lemma, E. D., De Vittorio, M., & Todaro, M. T. (2016). AlN-based flexible piezoelectric skin for energy harvesting from human motion. *Microelectronic Engineering, 159,* 174–178. https://doi.org/10.1016/j.mee.2016.03.041.
51. Zhao, J., & You, Z. (2014). A shoe-embedded piezoelectric energy harvester for wearable sensors. *Sensors, 14*(7), 12497–12510. https://doi.org/10.3390/s140712497.
52. Cao, W., Yu, W., & Huang, W. (2019). A Piezoelectric Energy Harvester for Wearable Applications. In W. K. Wong (Ed.), *Artificial Intelligence on Fashion and Textiles* (Vol. 849, pp. 61–67). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-99695-0_8.
53. Wen, S., & Xu, Q. (2018). Design of a novel piezoelectric energy harvester for scavenging energy from human walking. In *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (*AIM*) (pp. 792–797). Presented at the 2018 IEEE/ASME international conference on advanced intelligent mechatronics (AIM). https://doi.org/10.1109/aim.2018.8452343.
54. Qian, F., Xu, T.-B., & Zuo, L. (2018). Design, optimization, modeling and testing of a piezoelectric footwear energy harvester. *Energy Conversion and Management, 171,* 1352–1364. https://doi.org/10.1016/j.enconman.2018.06.069.
55. Wu, Y., Ma, F., Qu, J., & Qi, T. (2018). Enhanced mechanical and piezoelectric properties of BCZT-CuY/rGO-based nanogenerator for tiny energy harvesting. *Materials Letters, 231,* 20–23. https://doi.org/10.1016/j.matlet.2018.07.102.
56. Dong, W., Chen, F., Yang, M., Du, Z., Tang, J., & Zhang, D. (2017). Development of a highly efficient bridge-type mechanism based on negative stiffness. *Smart Materials and Structures, 26*(9), 095053. https://doi.org/10.1088/1361-665X/aa8102.
57. Lu, Q., Liu, L., Scarpa, F., Leng, J., & Liu, Y. (2018). A novel composite multi-layer piezoelectric energy harvester. *Composite Structures, 201,* 121–130. https://doi.org/10.1016/j.compstruct.2018.06.024.
58. Chen, S., Wang, L., Zhou, W., Musgrave, P., Xu, T.-B., & Zuo, L. (2015). Optimal design of force magnification frame of a piezoelectric stack energy harvester. In J. P. Lynch (Ed.) (p. 943516). Presented at the SPIE smart structures and materials + nondestructive evaluation and health monitoring, San Diego. https://doi.org/10.1117/12.2084284.
59. Granstrom, J., Feenstra, J., Sodano, H. A., & Farinholt, K. (2007). Energy harvesting from a backpack instrumented with piezoelectric shoulder straps. *Smart Materials and Structures, 16*(5), 1810. https://doi.org/10.1088/0964-1726/16/5/036.
60. Izadgoshasb, I., Lim, Y. Y., Lake, N., Tang, L., Padilla, R. V., & Kashiwao, T. (2018). Optimizing orientation of piezoelectric cantilever beam for harvesting energy from human walking. *Energy Conversion and Management, 161,* 66–73. https://doi.org/10.1016/j.enconman.2018.01.076.
61. Saida, M., Zaibi, G., Samet, M., & Kachouri, A. (2018). Design and Study of Piezoelectric Energy Harvesting Cantilever from Human Body. In *2018 15th International Multi-Conference on Systems, Signals Devices* (*SSD*) (pp. 164–168). Presented at the 2018 15th international multi-conference on systems, signals devices (SSD). https://doi.org/10.1109/ssd.2018.8570616.
62. Bai, Y., Tofel, P., Hadas, Z., Smilek, J., Losak, P., Skarvada, P., et al. (2018). Investigation of a cantilever structured piezoelectric energy harvester used for wearable devices with random vibration input. *Mechanical Systems and Signal Processing, 106,* 303–318. https://doi.org/10.1016/j.ymssp.2018.01.006.
63. Salim, M., Salim, D., Chandran, D., Aljibori, H. S., & Kherbeet, A. S. (2018). Review of nano piezoelectric devices in biomedicine applications. *Journal of Intelligent Material Systems and Structures, 29*(10), 2105–2121.
64. Piezoelectric field effect transistor and nanoforce sensor based on a single ZnO nanowire–nano letters (ACS Publications). https://pubs.acs.org/doi/abs/10.1021/nl061802g. Retrieved 30 Dec 2018.
65. Zhang, Z., Chen, Y., & Guo, J. (2019). ZnO nanorods patterned-textile using a novel hydrothermal method for sandwich structured-piezoelectric nanogenerator for human energy harvesting. *Physica E: Low-dimensional Systems and Nanostructures, 105,* 212–218. https://doi.org/10.1016/j.physe.2018.09.007.
66. Siddiqui, S., Lee, H. B., Kim, D.-I., Duy, L. T., Hanif, A., & Lee, N.-E. (2018). An omnidirectionally stretchable piezoelectric nanogenerator based on hybrid nanofibers and carbon electrodes for multimodal straining and human kinematics energy

harvesting. *Advanced Energy Materials, 8*(2), 1701520. https://doi.org/10.1002/aenm.201701520.
67. Kim, K.-B., Cho, J. Y., Jeon, D. H., Woo, S. B., Ryu, C. H., Ahn, J. H., et al. (2018). A biocompatible and flexible piezoelectric generator with high-quality boron nitride nanotubes from human running. *Nano Energy*. https://doi.org/10.1016/j.nanoen.2018.09.071.
68. Si, S. K., Karan, S. K., Paria, S., Maitra, A., Das, A. K., Bera, R., et al. (2018). A strategy to develop an efficient piezoelectric nanogenerator through ZTO assisted γ-phase nucleation of PVDF in ZTO/PVDF nanocomposite for harvesting bio-mechanical energy and energy storage application. *Materials Chemistry and Physics, 213,* 525–537. https://doi.org/10.1016/j.matchemphys.2018.04.013.
69. Dudem, B., Kim, D. H., Bharat, L. K., & Yu, J. S. (2018). Highly-flexible piezoelectric nanogenerators with silver nanowires and barium titanate embedded composite films for mechanical energy harvesting. *Applied Energy, 230,* 865–874. https://doi.org/10.1016/j.apenergy.2018.09.009.
70. Shenck, N. S., & Paradiso, J. A. (2001). Energy scavenging with shoe-mounted piezoelectrics. *IEEE Micro, 21*(3), 30–42. https://doi.org/10.1109/40.928763.
71. Rocha, J. G., Goncalves, L. M., Rocha, P. F., Silva, M. P., & Lanceros-Mendez, S. (2010). Energy harvesting from piezoelectric materials fully integrated in footwear. *IEEE Transactions on Industrial Electronics, 57*(3), 813–819. https://doi.org/10.1109/TIE.2009.2028360.
72. Mateu, L., & Moll, F. (2005). Optimum piezoelectric bending beam structures for energy harvesting using shoe inserts. *Journal of Intelligent Material Systems and Structures, 16*(10), 835–845. https://doi.org/10.1177/1045389X05055280.
73. Xia, H., & Shull, P. B. (2018). Preliminary testing of an angled sliding shoe for potential human energy harvesting applications. In *2018 2nd International Conference on Robotics and Automation Sciences* (*ICRAS*) (pp. 1–4). Presented at the 2018 2nd international conference on robotics and automation sciences (ICRAS), Wuhan, China: IEEE. https://doi.org/10.1109/icras.2018.8442419.
74. Cha, Y., & Seo, J. (2018). Energy harvesting from a piezoelectric slipper during walking. *Journal of Intelligent Material Systems and Structures, 29*(7), 1456–1463. https://doi.org/10.1177/1045389X17740962.
75. Ma, D., Lan, G., Xu, W., Hassan, M., & Hu, W. (2018). SEHS: Simultaneous energy harvesting and sensing using piezoelectric energy harvester. (:unav). https://doi.org/10.1109/iotdi.2018.00028.
76. Cao, J., Wang, W., Zhou, S., Inman, D. J., & Lin, J. (2015). Nonlinear time-varying potential bistable energy harvesting from human motion. *Applied Physics Letters, 107*(14), 143904. https://doi.org/10.1063/1.4932947.
77. Wang, W., Cao, J., Bowen, C. R., Zhou, S., & Lin, J. (2017). Optimum resistance analysis and experimental verification of nonlinear piezoelectric energy harvesting from human motions. *Energy, 118,* 221–230. https://doi.org/10.1016/j.energy.2016.12.035.
78. Li, Z., Yang, Z., Naguib, H., & Zu, J. (2018). Design and studies on a low-frequency truss-based compressive-mode piezoelectric energy harvester. *IEEE/ASME Transactions on Mechatronics, 23*(6), 2849–2858. https://doi.org/10.1109/TMECH.2018.2871781.
79. Almusallam, A., Luo, Z., Komolafe, A., Yang, K., Robinson, A., Torah, R., et al. (2017). Flexible piezoelectric nanocomposite films for kinetic energy harvesting from textiles. *Nano Energy, 33,* 146–156. https://doi.org/10.1016/j.nanoen.2017.01.037.
80. Talbourdet, A., Rault, F., Lemort, G., Cochrane, C., Devaux, E., & Campagne, C. (2018). 3D interlock design 100% PVDF piezoelectric to improve energy harvesting. *Smart Materials and Structures, 27*(7), 075010. https://doi.org/10.1088/1361-665X/aab865.
81. Ravi, S. K., Wu, T., Udayagiri, V. S., Vu, X. M., Wang, Y., Jones, M. R., et al. (2018). Photosynthetic bioelectronic sensors for touch perception, UV-detection, and nanopower generation: Toward self-powered E-skins. *Advanced Materials, 30*(39), 1802290. https://doi.org/10.1002/adma.201802290.
82. Guo, R., Wang, X., Yu, W., Tang, J., & Liu, J. (2018). A highly conductive and stretchable wearable liquid metal electronic skin for long-term conformable health monitoring. *Science China Technological Sciences, 61*(7), 1031–1037. https://doi.org/10.1007/s11431-018-9253-9.
83. Kim, S.-W., Lee, Y., Park, J., Kim, S., Chae, H., Ko, H., et al. (2017). A triple-mode flexible e-skin sensor interface for multipurpose wearable applications. *Sensors, 18*(2), 78. https://doi.org/10.3390/s18010078.
84. Dutta, B., Kar, E., Bose, N., & Mukherjee, S. (2018). NiO@SiO_2/PVDF: A flexible polymer nanocomposite for a high performance human body motion-based energy harvester and tactile e-skin mechanosensor. *ACS Sustainable Chemistry and Engineering, 6*(8), 10505–10516. https://doi.org/10.1021/acssuschemeng.8b01851.
85. He, Z., Gao, B., Li, T., Liao, J., Liu, B., Liu, X., et al. (2018). Piezoelectric-driven self-powered patterned electrochromic supercapacitor for human motion energy harvesting. *ACS Sustainable Chemistry and Engineering*. https://doi.org/10.1021/acssuschemeng.8b05606.
86. Zhao, T., Fu, Y., He, H., Dong, C., Zhang, L., Zeng, H., et al. (2018). Self-powered gustation electronic skin for mimicking taste buds based on piezoelectric–enzymatic reaction coupling process. *Nanotechnology, 29*(7), 075501. https://doi.org/10.1088/1361-6528/aaa2b9.
87. Zhang, L., Fu, Y., Xing, L., Liu, B., Zhang, Y., & Xue, X. (2017). A self-powered flexible vision electronic-skin for image recognition based on a pixel-addressable matrix of piezophototronic ZnO nanowire arrays. *Journal of Materials Chemistry C, 5*(24), 6005–6013. https://doi.org/10.1039/C7TC01842H.
88. He, H., Fu, Y., Zang, W., Wang, Q., Xing, L., Zhang, Y., et al. (2017). A flexible self-powered T-ZnO/PVDF/fabric electronic-skin with multi-functions of tactile-perception, atmosphere-detection and self-clean. *Nano Energy, 31,* 37–48. https://doi.org/10.1016/j.nanoen.2016.11.020.
89. Shi, B., Li, Z., & Fan, Y. (2018). Implantable energy-harvesting devices. *Advanced Materials, 30*(44), 1801511. https://doi.org/10.1002/adma.201801511.
90. Dagdeviren, C., Yang, B. D., Su, Y., Tran, P. L., Joe, P., Anderson, E., et al. (2014). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. *Proceedings of the National Academy of Sciences, 111*(5), 1927–1932. https://doi.org/10.1073/pnas.1317233111.
91. Wu, M., Wang, Y., Gao, S., Wang, R., Ma, C., Tang, Z., et al. (2019). Solution-synthesized chiral piezoelectric selenium nanowires for wearable self-powered human-integrated monitoring. *Nano Energy, 56,* 693–699. https://doi.org/10.1016/j.nanoen.2018.12.003.
92. Pillatsch, P., Yeatman, E. M., & Holmes, A. S. (2012). A scalable piezoelectric impulse-excited energy harvester for human body excitation. *Smart Materials and Structures, 21*(11), 115018. https://doi.org/10.1088/0964-1726/21/11/115018.
93. Pillatsch, P., Yeatman, E. M., & Holmes, A. S. (2014). A piezoelectric frequency up-converting energy harvester with rotating proof mass for human body applications. *Sensors and*

Actuators, A: Physical, 206, 178–185. https://doi.org/10.1016/j.sna.2013.10.003.

94. Kuang, Y., Yang, Z., & Zhu, M. (2016). Design and characterisation of a piezoelectric knee-joint energy harvester with frequency up-conversion through magnetic plucking. *Smart Materials and Structures, 25*(8), 085029.
95. Fu, H., & Yeatman, E. M. (2017). A methodology for low-speed broadband rotational energy harvesting using piezoelectric transduction and frequency up-conversion. *Energy, 125,* 152–161.
96. Luo, Z., Zhu, D., & Beeby, S. P. (2015). Multilayer ferroelectret-based energy harvesting insole. *Journal of Physics: Conference Series, 660,* 012118. https://doi.org/10.1088/1742-6596/660/1/012118.
97. Zhao, Y., Fan, H., Ren, X., Long, C., Liu, G., & Liu, Z. (2016). Lead-free Bi La Ti FeO (x = 0, 1) nanofibers toward wool keratin-based biocompatible piezoelectric nanogenerators. *Journal of Materials Chemistry C, 4*(30), 7324–7331. https://doi.org/10.1039/c6tc01828a.
98. Kim, K. N., Chun, J., Chae, S. A., Ahn, C. W., Kim, I. W., Kim, S.-W., et al. (2015). Silk fibroin-based biodegradable piezoelectric composite nanogenerators using lead-free ferroelectric nanoparticles. *Nano Energy, 14,* 87–94. https://doi.org/10.1016/j.nanoen.2015.01.004.
99. Kim, J., Lee, H., & Kim, H. S. (2010). Beam vibration control using cellulose-based electro-active paper sensor. *International Journal of Precision Engineering and Manufacturing, 11*(6), 823–827.
100. Abas, Z., Kim, H. S., Zhai, L., & Kim, J. (2015). Experimental study of vibrational energy harvesting using Electro-Active paper. *International Journal of Precision Engineering and Manufacturing, 16*(6), 1187–1193.
101. Yun, G., Kim, H. S., & Kim, J. (2008). Blocked force measurement of an electro-active paper actuator using a cantilevered force transducer. *Smart Materials and Structures, 17*(2), 025021.
102. Kim, J.-H., Shim, B. S., Kim, H. S., Lee, Y.-J., Min, S.-K., Jang, D., et al. (2015). Review of nanocellulose for sustainable future materials. *International Journal of Precision Engineering and Manufacturing-Green Technology, 2*(2), 197–213.
103. Costilla-Reyes, A., Abuellil, A., Estrada-Lopez, J. J., Carreon-Bautista, S., & Sanchez-Sinencio, E. (2018). Reconfigurable system for electromagnetic energy harvesting with inherent activity sensing capabilities for wearable technology. *IEEE Transactions on Circuits and Systems II: Express Briefs*. https://doi.org/10.1109/tcsii.2018.2884613.
104. Park, H., & Kim, J. (2016). Electromagnetic induction energy harvester for high-speed railroad applications. *International Journal of Precision Engineering and Manufacturing-Green Technology, 3*(1), 41–48.
105. Invernizzi, F., Dulio, S., Patrini, M., Guizzetti, G., & Mustarelli, P. (2016). Energy harvesting from human motion: Materials and techniques. *Chemical Society Reviews, 45*(20), 5455–5473. https://doi.org/10.1039/C5CS00812C.
106. Mann, B. P., Barton, D. A., & Owens, B. A. (2012). Uncertainty in performance for linear and nonlinear energy harvesting strategies. *Journal of Intelligent Material Systems and Structures, 23*(13), 1451–1460. https://doi.org/10.1177/1045389X12439639.
107. Kucab, K., Górski, G., & Mizia, J. (2015). Energy harvesting in the nonlinear electromagnetic system. *The European Physical Journal Special Topics, 224*(14–15), 2909–2918. https://doi.org/10.1140/epjst/e2015-02597-1.
108. Owens, B. A. M., & Mann, B. P. (2012). Linear and nonlinear electromagnetic coupling models in vibration-based energy harvesting. *Journal of Sound and Vibration, 331*(4), 922–937. https://doi.org/10.1016/j.jsv.2011.10.026.
109. Fu, H., & Yeatman, E. M. (2018). Comparison and scaling effects of rotational micro-generators using electromagnetic and piezoelectric transduction. *Energy Technology, 6*(11), 2220–2231. https://doi.org/10.1002/ente.201800151.
110. Liu, H., Hou, C., Lin, J., Li, Y., Shi, Q., Chen, T., et al. (2018). A non-resonant rotational electromagnetic energy harvester for low-frequency and irregular human motion. *Applied Physics Letters, 113*(20), 203901. https://doi.org/10.1063/1.5053945.
111. Lin, J., Liu, H., Chen, T., Yang, Z., & Sun, L. (2017). A rotational wearable energy harvester for human motion. In *2017 IEEE 17th International conference on nanotechnology* (*IEEE-NANO*) (pp. 22–25). Presented at the 2017 IEEE 17th international conference on nanotechnology (IEEE-NANO), Pittsburgh, PA, USA: IEEE. https://doi.org/10.1109/nano.2017.8117409.
112. Zhu, D., Duarte-Rabelo, I., Ayala-Garcia, I. N., & Somov, A. (2018). An electromagnetic in-shoe energy harvester using wave springs. In *2018 IEEE industrial cyber-physical systems* (*ICPS*) (pp. 659–663). Presented at the 2018 IEEE industrial cyber-physical systems (ICPS), St. Petersburg: IEEE. https://doi.org/10.1109/icphys.2018.8390785.
113. Wang, W., Cao, J., Zhang, N., Lin, J., & Liao, W.-H. (2017). Magnetic-spring based energy harvesting from human motions: Design, modeling and experiments. *Energy Conversion and Management, 132,* 189–197. https://doi.org/10.1016/j.enconman.2016.11.026.
114. Ylli, K., Hoffmann, D., Willmann, A., Becker, P., Folkmer, B., & Manoli, Y. (2015). Energy harvesting from human motion: Exploiting swing and shock excitations. *Smart Materials and Structures, 24*(2), 025029. https://doi.org/10.1088/0964-1726/24/2/025029.
115. Halim, M. A., Cho, H., & Park, J. Y. (2015). Design and experiment of a human-limb driven, frequency up-converted electromagnetic energy harvester. *Energy Conversion and Management, 106,* 393–404. https://doi.org/10.1016/j.enconman.2015.09.065.
116. Anjum, M. U., Fida, A., Ahmad, I., & Iftikhar, A. (2018). A broadband electromagnetic type energy harvester for smart sensor devices in biomedical applications. *Sensors and Actuators, A: Physical, 277,* 52–59. https://doi.org/10.1016/j.sna.2018.05.001.
117. Zhang, Q., Wang, Y., & Kim, E. S. (2015). Electromagnetic energy harvester with flexible coils and magnetic spring for 1–10 Hz resonance. *Journal of Microelectromechanical Systems, 24*(4), 1193–1206. https://doi.org/10.1109/jmems.2015.2393911.
118. Halim, M. A., Rantz, R., Zhang, Q., Gu, L., Yang, K., & Roundy, S. (2018). An electromagnetic rotational energy harvester using sprung eccentric rotor, driven by pseudo-walking motion. *Applied Energy, 217,* 66–74. https://doi.org/10.1016/j.apenergy.2018.02.093.
119. Zhang, Q., Gu, L., Yang, K., Halim, M. A., Rantz, R., & Roundy, S. (2016). Kinetic energy harvesting using improved eccentric rotor architecture for wearable sensors. In *2016 IEEE SENSORS* (pp. 1–3). Presented at the 2016 IEEE SENSORS, Orlando: IEEE. https://doi.org/10.1109/icsens.2016.7808949.
120. Miyoshi, T., Adachi, M., Tanaka, Y., & Suzuki, Y. (2018). Low-profile Rotational Electret Energy Harvester for Battery-less Wearable Device. In *2018 IEEE/ASME international conference on advanced intelligent mechatronics* (*AIM*) (pp. 391–394). Presented at the 2018 IEEE/ASME international conference on advanced intelligent mechatronics (AIM), Auckland: IEEE. https://doi.org/10.1109/aim.2018.8452249.
121. Xue, T., Williams, S., Rantz, R., Halim, M. A., & Roundy, S. (2018). System modeling, characterization, and design considerations for generators in commercial watches with application to energy harvesting for wearables. *IEEE/ASME Transactions on Mechatronics, 23*(5), 2515–2524. https://doi.org/10.1109/TMECH.2018.2865307.

122. Zhou, M., Al-Furjan, M. S. H., Zou, J., & Liu, W. (2018). A review on heat and mechanical energy harvesting from human—Principles, prototypes and perspectives. *Renewable and Sustainable Energy Reviews, 82,* 3582–3609. https://doi.org/10.1016/j.rser.2017.10.102.
123. Liu, L., Tang, W., Deng, C., Chen, B., Han, K., Zhong, W., et al. (2018). Self-powered versatile shoes based on hybrid nanogenerators. *Nano Research, 11*(8), 3972–3978. https://doi.org/10.1007/s12274-018-1978-z.
124. Ren, X., Fan, H., Wang, C., Ma, J., Lei, S., Zhao, Y., et al. (2017). Magnetic force driven noncontact electromagnetic-triboelectric hybrid nanogenerator for scavenging biomechanical energy. *Nano Energy, 35,* 233–241. https://doi.org/10.1016/j.nanoen.2017.03.047.
125. Halim, M. A., Cho, H., Salauddin, Md, & Park, J. Y. (2016). A miniaturized electromagnetic vibration energy harvester using flux-guided magnet stacks for human-body-induced motion. *Sensors and Actuators, A: Physical, 249,* 23–31. https://doi.org/10.1016/j.sna.2016.08.008.
126. Halim, M. A., Rantz, R., Zhang, Q., Gu, L., Yang, K., & Roundy, S. (2018). Modeling and experimental analysis of a wearable energy harvester that exploits human-body motion. In *Presented at 2018 IEEE SENSORS*. https://doi.org/10.1109/ICSENS.2018.8589632
127. Magno, M., Kneubuhler, D., Mayer, P., & Benini, L. (2018). Micro Kinetic Energy Harvesting for Autonomous Wearable Devices. In *2018 International symposium on power electronics, electrical drives, automation and motion* (*SPEEDAM*) (pp. 105–110). Presented at the 2018 international symposium on power electronics, electrical drives, automation and motion (SPEEDAM), Amalfi, Italy: IEEE. https://doi.org/10.1109/speedam.2018.8445342.
128. Wu, S., Luk, P. C. K., Li, C., Zhao, X., Jiao, Z., & Shang, Y. (2017). An electromagnetic wearable 3-DoF resonance human body motion energy harvester using ferrofluid as a lubricant. *Applied Energy, 197,* 364–374. https://doi.org/10.1016/j.apenergy.2017.04.006.
129. Maharjan, P., Cho, H., Rasel, M. S., Salauddin, Md, & Park, J. Y. (2018). A fully enclosed, 3D printed, hybridized nanogenerator with flexible flux concentrator for harvesting diverse human biomechanical energy. *Nano Energy, 53,* 213–224. https://doi.org/10.1016/j.nanoen.2018.08.034.
130. Salauddin, M., & Park, J. Y. (2017). Design and experiment of human hand motion driven electromagnetic energy harvester using dual Halbach magnet array. *Smart Materials and Structures, 26*(3), 035011. https://doi.org/10.1088/1361-665X/aa573f.
131. Berdy, D. F., Valentino, D. J., & Peroulis, D. (2015). Kinetic energy harvesting from human walking and running using a magnetic levitation energy harvester. *Sensors and Actuators, A: Physical, 222,* 262–271. https://doi.org/10.1016/j.sna.2014.12.006.
132. Fan, K., Cai, M., Liu, H., & Zhang, Y. (2019). Capturing energy from ultra-low frequency vibrations and human motion through a monostable electromagnetic energy harvester. *Energy, 169,* 356–368. https://doi.org/10.1016/j.energy.2018.12.053.
133. Fan, K., Zhang, Y., Liu, H., Cai, M., & Tan, Q. (2019). A nonlinear two-degree-of-freedom electromagnetic energy harvester for ultra-low frequency vibrations and human body motions. *Renewable Energy, 138,* 292–302.
134. Halim, M. A., & Park, J. Y. (2013). A frequency up-converted electromagnetic energy harvester using human hand-shaking. In *Journal of Physics: Conference Series* (Vol. 476, p. 012119). IOP Publishing.
135. Zhang, K., Wang, X., Yang, Y., & Wang, Z. L. (2015). Hybridized electromagnetic-triboelectric nanogenerator for scavenging biomechanical energy for sustainably powering wearable electronics. *ACS Nano, 9*(4), 3521–3529. https://doi.org/10.1021/nn507455f.
136. Fan, F.-R., Tian, Z.-Q., & Wang, Z. L. (2012). Flexible triboelectric generator. *Nano Energy, 1*(2), 328–334.
137. Zheng, Q., Shi, B., Li, Z., & Wang, Z. L. (2017). Recent progress on piezoelectric and triboelectric energy harvesters in biomedical systems. *Advanced Science, 4*(7), 1700029. https://doi.org/10.1002/advs.201700029.
138. Liu, Z., Li, H., Shi, B., Fan, Y., Wang, Z. L., & Li, Z. (2019). Wearable and implantable triboelectric nanogenerators. *Advanced Functional Materials, 29,* 1808820.
139. Zhu, G., Pan, C., Guo, W., Chen, C.-Y., Zhou, Y., Yu, R., et al. (2012). Triboelectric-generator-driven pulse electrodeposition for micropatterning. *Nano Letters, 12*(9), 4960–4965. https://doi.org/10.1021/nl302560k.
140. Yang, Y., Zhang, H., Lin, Z.-H., Zhou, Y. S., Jing, Q., Su, Y., et al. (2013). Human skin based triboelectric nanogenerators for harvesting biomechanical energy and as self-powered active tactile sensor system. *ACS Nano, 7*(10), 9213–9222. https://doi.org/10.1021/nn403838y.
141. Bai, P., Zhu, G., Lin, Z.-H., Jing, Q., Chen, J., Zhang, G., et al. (2013). Integrated multilayered triboelectric nanogenerator for harvesting biomechanical energy from human motions. *ACS Nano, 7*(4), 3713–3719. https://doi.org/10.1021/nn4007708.
142. Zhu, G., Bai, P., Chen, J., & Lin Wang, Z. (2013). Power-generating shoe insole based on triboelectric nanogenerators for self-powered consumer electronics. *Nano Energy, 2*(5), 688–692. https://doi.org/10.1016/j.nanoen.2013.08.002.
143. Yang, W., Chen, J., Zhu, G., Yang, J., Bai, P., Su, Y., et al. (2013). Harvesting energy from the natural vibration of human walking. *ACS Nano, 7*(12), 11317–11324. https://doi.org/10.1021/nn405175z.
144. Hou, T.-C., Yang, Y., Zhang, H., Chen, J., Chen, L.-J., & Lin Wang, Z. (2013). Triboelectric nanogenerator built inside shoe insole for harvesting walking energy. *Nano Energy, 2*(5), 856–862. https://doi.org/10.1016/j.nanoen.2013.03.001.
145. Kim, H.-J., Yim, E.-C., Kim, J.-H., Kim, S.-J., Park, J.-Y., & Oh, I.-K. (2017). Bacterial nano-cellulose triboelectric nanogenerator. *Nano Energy, 33,* 130–137.
146. Kim, H.-J., Kim, J.-H., Jun, K.-W., Kim, J.-H., Seung, W.-C., Kwon, O. H., et al. (2016). Silk nanofiber-networked bio-triboelectric generator: Silk Bio-TEG. *Advanced Energy Materials, 6*(8), 1–6.
147. Chen, H., Song, Y., Cheng, X., & Zhang, H. (2019). Self-powered electronic skin based on the triboelectric generator. *Nano Energy, 56,* 252–268. https://doi.org/10.1016/j.nanoen.2018.11.061.
148. Zhu, G., Chen, J., Zhang, T., Jing, Q., & Wang, Z. L. (2014). Radial-arrayed rotary electrification for high performance triboelectric generator. *Nature Communications*. https://doi.org/10.1038/ncomms4426.
149. Lin, L., Wang, S., Xie, Y., Jing, Q., Niu, S., Hu, Y., et al. (2013). Segmentally structured disk triboelectric nanogenerator for harvesting rotational mechanical energy. *Nano Letters, 13*(6), 2916–2923. https://doi.org/10.1021/nl4013002.
150. Song, Y., Wang, H., Cheng, X., Li, G., Chen, X., Chen, H., et al. (2019). High-efficiency self-charging smart bracelet for portable electronics. *Nano Energy, 55,* 29–36. https://doi.org/10.1016/j.nanoen.2018.10.045.
151. Pu, X., Song, W., Liu, M., Sun, C., Du, C., Jiang, C., et al. (2016). Wearable power-textiles by integrating fabric triboelectric nanogenerators and fiber-shaped dye-sensitized solar cells. *Advanced Energy Materials, 6*(20), 1601048. https://doi.org/10.1002/aenm.201601048.
152. Shao, J., Jiang, T., Tang, W., Xu, L., Kim, T. W., Wu, C., et al. (2018). Studying about applied force and the output performance

of sliding-mode triboelectric nanogenerators. *Nano Energy, 48,* 292–300. https://doi.org/10.1016/j.nanoen.2018.03.067.
153. Zhu, G., Zhou, Y. S., Bai, P., Meng, X. S., Jing, Q., Chen, J., et al. (2014). A shape-adaptive thin-film-based approach for 50% high-efficiency energy generation through micro-grating sliding electrification. *Advanced Materials, 26*(23), 3788–3796. https://doi.org/10.1002/adma.201400021.
154. Lai, Y.-C. (2019). Nanowires for triboelectric nanogenerators. In *Nanowire Electronics* (pp. 353–365). Springer.
155. Chen, S. W., Cao, X., Wang, N., Ma, L., Zhu, H. R., Willander, M., et al. (2017). An ultrathin flexible single-electrode triboelectric-nanogenerator for mechanical energy harvesting and instantaneous force sensing. *Advanced Energy Materials, 7*(1), 1601255. https://doi.org/10.1002/aenm.201601255.
156. Cheng, X., Meng, B., Zhang, X., Han, M., Su, Z., & Zhang, H. (2015). Wearable electrode-free triboelectric generator for harvesting biomechanical energy. *Nano Energy, 12,* 19–25.
157. Zhang, H., Yang, Y., Hou, T.-C., Su, Y., Hu, C., & Wang, Z. L. (2013). Triboelectric nanogenerator built inside clothes for self-powered glucose biosensors. *Nano Energy, 2*(5), 1019–1024. https://doi.org/10.1016/j.nanoen.2013.03.024.
158. Yi, F., Lin, L., Niu, S., Yang, P. K., Wang, Z., Chen, J., et al. (2015). Stretchable-rubber-based triboelectric nanogenerator and its application as self-powered body motion sensors. *Advanced Functional Materials, 25*(24), 3688–3696. https://doi.org/10.1002/adfm.201500428.
159. Niu, S., Liu, Y., Wang, S., Lin, L., Zhou, Y. S., Hu, Y., et al. (2014). Theoretical investigation and structural optimization of single-electrode triboelectric nanogenerators. *Advanced Functional Materials, 24*(22), 3332–3340. https://doi.org/10.1002/adfm.201303799.
160. Zhu, G., Yang, W. Q., Zhang, T., Jing, Q., Chen, J., Zhou, Y. S., et al. (2014). Self-powered, ultrasensitive, flexible tactile sensors based on contact electrification. *Nano Letters, 14*(6), 3208–3213. https://doi.org/10.1021/nl5005652.
161. Hofmann, M., & Schellnhuber, H. J. (2010). Ocean acidification: A millennial challenge. *Energy and Environmental Science, 3*(12), 1883. https://doi.org/10.1039/c000820f.
162. Xie, Y., Wang, S., Niu, S., Lin, L., Jing, Q., Yang, J., et al. (2014). Grating-structured freestanding triboelectric-layer nanogenerator for harvesting mechanical energy at 85% total conversion efficiency. *Advanced Materials, 26*(38), 6599–6607.
163. Guo, H., Chen, J., Yeh, M.-H., Fan, X., Wen, Z., Li, Z., et al. (2015). An ultrarobust high-performance triboelectric nanogenerator based on charge replenishment. *ACS Nano, 9*(5), 5577–5584.
164. Zhang, C., Tang, W., Pang, Y., Han, C., & Wang, Z. L. (2015). Active micro-actuators for optical modulation based on a planar sliding triboelectric nanogenerator. *Advanced Materials, 27*(4), 719–726.
165. Wang, S., Niu, S., Yang, J., Lin, L., & Wang, Z. L. (2014). Quantitative measurements of vibration amplitude using a contact-mode freestanding triboelectric nanogenerator. *ACS Nano, 8*(12), 12004–12013.
166. Cherenack, K., Zysset, C., Kinkeldei, T., Münzenrieder, N., & Tröster, G. (2010). Woven electronic fibers with sensing and display functions for smart textiles. *Advanced Materials, 22*(45), 5178–5182.
167. Zeng, W., Shu, L., Li, Q., Chen, S., Wang, F., & Tao, X.-M. (2014). Fiber-based wearable electronics: A review of materials, fabrication, devices, and applications. *Advanced Materials, 26*(31), 5310–5336.
168. Li, Z., & Wang, Z. L. (2011). Air/liquid-pressure and heartbeat-driven flexible fiber nanogenerators as a micro/nano-power source or diagnostic sensor. *Advanced Materials, 23*(1), 84–89.
169. Tian, Z., He, J., Chen, X., Zhang, Z., Wen, T., Zhai, C., et al. (2017). Performance-boosted triboelectric textile for harvesting human motion energy. *Nano Energy, 39,* 562–570. https://doi.org/10.1016/j.nanoen.2017.06.018.
170. Xiong, J., Cui, P., Chen, X., Wang, J., Parida, K., Lin, M.-F., et al. (2018). Skin-touch-actuated textile-based triboelectric nanogenerator with black phosphorus for durable biomechanical energy harvesting. *Nature Communications*. https://doi.org/10.1038/s41467-018-06759-0.
171. Kwak, S. S., Kim, H., Seung, W., Kim, J., Hinchet, R., & Kim, S.-W. (2017). Fully stretchable textile triboelectric nanogenerator with knitted fabric structures. *ACS Nano, 11*(11), 10733–10741. https://doi.org/10.1021/acsnano.7b05203.
172. Seung, W., Gupta, M. K., Lee, K. Y., Shin, K.-S., Lee, J.-H., Kim, T. Y., et al. (2015). Nanopatterned textile-based wearable triboelectric nanogenerator. *ACS Nano, 9*(4), 3501–3509. https://doi.org/10.1021/nn507221f.
173. Zhao, Z., Yan, C., Liu, Z., Fu, X., Peng, L.-M., Hu, Y., et al. (2016). Machine-washable textile triboelectric nanogenerators for effective human respiratory monitoring through loom weaving of metallic yarns. *Advanced Materials, 28*(46), 10267–10274.
174. Li, Z., Shen, J., Abdalla, I., Yu, J., & Ding, B. (2017). Nanofibrous membrane constructed wearable triboelectric nanogenerator for high performance biomechanical energy harvesting. *Nano Energy, 36,* 341–348.
175. Roundy, S., Wright, P. K., & Rabaey, J. M. (2003). Energy scavenging for wireless sensor networks. *Norwell*, 45–47.
176. Miao, P., Holmes, A. S., Yeatman, E. M., Green, T. C., & Mitcheson, P. D. (2004). Micro-machined variable capacitors for power generation. In *Conference Series-Institute of Physics* (Vol. 178, pp. 53–58). Philadelphia; Institute of Physics; 1999.
177. Miao, P., Mitcheson, P. D., Holmes, A. S., Yeatman, E. M., Green, T. C., & Stark, B. H. (2006). MEMS inertial power generators for biomedical applications. *Microsystem Technologies, 12*(10–11), 1079–1083.
178. Shen, J., Li, Z., Yu, J., & Ding, B. (2017). Humidity-resisting triboelectric nanogenerator for high performance biomechanical energy harvesting. *Nano Energy, 40,* 282–288.
179. Li, S., Wang, J., Peng, W., Lin, L., Zi, Y., Wang, S., et al. (2017). Sustainable energy source for wearable electronics based on multilayer elastomeric triboelectric nanogenerators. *Advanced Energy Materials, 7*(13), 1602832.
180. Zhu, Y., Yang, B., Liu, J., Wang, X., Wang, L., Chen, X., et al. (2016). A flexible and biocompatible triboelectric nanogenerator with tunable internal resistance for powering wearable devices. *Scientific Reports, 6,* 22233.
181. Wang, Z. L. (2013). Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors. *ACS Nano, 7*(11), 9533–9557.
182. Yang, W., Chen, J., Wen, X., Jing, Q., Yang, J., Su, Y., et al. (2014). Triboelectrification based motion sensor for human-machine interfacing. *ACS Applied Materials and Interfaces, 6*(10), 7479–7484.
183. Pu, X., Guo, H., Chen, J., Wang, X., Xi, Y., Hu, C., et al. (2017). Eye motion triggered self-powered mechanosensational communication system using triboelectric nanogenerator. *Science Advances, 3*(7), e1700694.
184. Dhakar, L., Pitchappa, P., Tay, F. E. H., & Lee, C. (2016). An intelligent skin based self-powered finger motion sensor integrated with triboelectric nanogenerator. *Nano Energy, 19,* 532–540.
185. Wang, L., & Daoud, W. A. (2018). Highly flexible and transparent polyionic-skin triboelectric nanogenerator for biomechanical motion harvesting. *Advanced Energy Materials, 12,* 1803183.
186. Lai, Y.-C., Deng, J., Niu, S., Peng, W., Wu, C., Liu, R., et al. (2016). Electric eel-skin-inspired mechanically durable and

super-stretchable nanogenerator for deformable power source and fully autonomous conformable electronic-skin applications. *Advanced Materials, 28*(45), 10024–10032.
187. Jiang, Q., Wu, C., Wang, Z., Wang, A. C., He, J.-H., Wang, Z. L., et al. (2018). MXene electrochemical microsupercapacitor integrated with triboelectric nanogenerator as a wearable self-charging power unit. *Nano Energy, 45,* 266–272.
188. Rapoport, B. I., Kedzierski, J. T., & Sarpeshkar, R. (2012). A glucose fuel cell for implantable brain–machine interfaces. *PLoS One, 7*(6), e38436.
189. Occhiuzzi, C., Contri, G., & Marrocco, G. (2012). Design of implanted RFID tags for passive sensing of human body: The STENTag. *IEEE Transactions on Antennas and Propagation, 60*(7), 3146–3154.
190. Ding, X., Cao, H., Zhang, X., Li, M., & Liu, Y. (2018). Large scale triboelectric nanogenerator and self-powered flexible sensor for human sleep monitoring. *Sensors, 18*(6), 1713.
191. Ma, Y., Zheng, Q., Liu, Y., Shi, B., Xue, X., Ji, W., et al. (2016). Self-powered, one-stop, and multifunctional implantable triboelectric active sensor for real-time biomedical monitoring. *Nano Letters, 16*(10), 6042–6051.
192. Xu, W., Wong, M.-C., & Hao, J. (2019). Strategies and progress on improving robustness and reliability of triboelectric nanogenerators. *Nano Energy, 55,* 203–215. https://doi.org/10.1016/j.nanoen.2018.10.073.
193. Zhou, Q., Lee, K., Kim, K. N., Park, J. G., Pan, J., Bae, J., et al. (2019). High humidity- and contamination-resistant triboelectric nanogenerator with superhydrophobic interface. *Nano Energy, 57,* 903–910. https://doi.org/10.1016/j.nanoen.2018.12.091.
194. Xu, W., Huang, L.-B., & Hao, J. (2017). Fully self-healing and shape-tailorable triboelectric nanogenerators based on healable polymer and magnetic-assisted electrode. *Nano Energy, 40,* 399–407. https://doi.org/10.1016/j.nanoen.2017.08.045.
195. Zheng, Q., Jin, Y., Liu, Z., Ouyang, H., Li, H., Shi, B., et al. (2016). Robust multilayered encapsulation for high-performance triboelectric nanogenerator in harsh environment. *ACS Applied Materials and Interfaces, 8*(40), 26697–26703. https://doi.org/10.1021/acsami.6b06866.
196. Cho, H., Chung, J., Shin, G., Sim, J.-Y., Kim, D. S., Lee, S., et al. (2019). Toward sustainable output generation of liquid–solid contact triboelectric nanogenerators: The role of hierarchical structures. *Nano Energy, 56,* 56–64. https://doi.org/10.1016/j.nanoen.2018.11.039.
197. Lim, G.-H., Kwak, S. S., Kwon, N., Kim, T., Kim, H., Kim, S. M., et al. (2017). Fully stretchable and highly durable triboelectric nanogenerators based on gold-nanosheet electrodes for self-powered human-motion detection. *Nano Energy, 42,* 300–306.
198. He, X., Zi, Y., Guo, H., Zheng, H., Xi, Y., Wu, C., et al. (2017). A highly stretchable fiber-based triboelectric nanogenerator for self-powered wearable electronics. *Advanced Functional Materials, 27*(4), 1604378.
199. Zhang, K., Wang, Z. L., & Yang, Y. (2016). Conductive fabric-based stretchable hybridized nanogenerator for scavenging biomechanical energy. *ACS Nano, 10*(4), 4728–4734.
200. Wen, Z., Yang, Y., Sun, N., Li, G., Liu, Y., Chen, C., et al. (2018). A wrinkled PEDOT: PSS film based stretchable and transparent triboelectric nanogenerator for wearable energy harvesters and active motion sensors. *Advanced Functional Materials, 28*(37), 1803684.
201. Chen, X., Miao, L., Guo, H., Chen, H., Song, Y., Su, Z., et al. (2018). Waterproof and stretchable triboelectric nanogenerator for biomechanical energy harvesting and self-powered sensing. *Applied Physics Letters, 112*(20), 203902.
202. Yan, S., Lu, J., Song, W., & Xiao, R. (2018). Flexible triboelectric nanogenerator based on cost-effective thermoplastic polymeric nanofiber membranes for body-motion energy harvesting with high humidity-resistance. *Nano Energy, 48,* 248–255.
203. Yu, A., Pu, X., Wen, R., Liu, M., Zhou, T., Zhang, K., et al. (2017). Core–shell-yarn-based triboelectric nanogenerator textiles as power cloths. *ACS Nano, 11*(12), 12764–12771.
204. Li, W., Torres, D., Wang, T., Wang, C., & Sepúlveda, N. (2016). Flexible and biocompatible polypropylene ferroelectret nanogenerator (FENG): On the path toward wearable devices powered by human motion. *Nano Energy, 30,* 649–657. https://doi.org/10.1016/j.nanoen.2016.10.007.
205. Wang, Z. L. (2015). Triboelectric nanogenerators as new energy technology and self-powered sensors—Principles, problems and perspectives. *Faraday Discussions, 176,* 447–458.
206. Luo, Z., Zhu, D., & Beeby, S. P. (2015). Multilayer ferroelectret-based energy harvesting insole. In *Journal of Physics: Conference Series* (Vol. 660, p. 012118). IOP Publishing.
207. Khan, F., Sassani, F., & Stoeber, B. (2014). Nonlinear behaviour of membrane type electromagnetic energy harvester under harmonic and random vibrations. *Microsystem Technologies, 20*(7), 1323–1335.
208. Boisseau, S., Despesse, G., & Seddik, B. A. (2012). Electrostatic conversion for vibration energy harvesting **(arXiv preprint)**. arXiv:1210.5191.
209. Roundy, S., Wright, P. K., & Rabaey, J. M. (2003). Energy scavenging for wireless sensor networks. *Norwell*, 45–47.
210. Ma, D., Lan, G., Xu, W., Hassan, M., & Hu, W. (2018). SEHS: Simultaneous Energy Harvesting and Sensing Using Piezoelectric Energy Harvester. In *2018 IEEE/ACM Third International Conference on Internet-of-Things Design and Implementation (IoTDI)* (pp. 201–212). Presented at the 2018 IEEE/ACM third international conference on internet-of-things design and implementation (IoTDI), Orlando, FL: IEEE. https://doi.org/10.1109/iotdi.2018.00028.
211. Izadgoshasb, I., Lim, Y. Y., Tang, L., Padilla, R. V., Tang, Z. S., & Sedighi, M. (2019). Improving efficiency of piezoelectric based energy harvesting from human motions using double pendulum system. *Energy Conversion and Management, 184,* 559–570. https://doi.org/10.1016/j.enconman.2019.02.001.
212. Caliò, R., Rongala, U., Camboni, D., Milazzo, M., Stefanini, C., de Petris, G., et al. (2014). Piezoelectric energy harvesting solutions. *Sensors, 14*(3), 4755–4790. https://doi.org/10.3390/s140304755.
213. Pillatsch, P., Yeatman, E. M., Holmes, A. S., & Wright, P. K. (2016). Wireless power transfer system for a human motion energy harvester. *Sensors and Actuators, A: Physical, 244,* 77–85. https://doi.org/10.1016/j.sna.2016.04.022.
214. Luciano, V., Sardini, E., Serpelloni, M., & Baronio, G. (2014). An energy harvesting converter to power sensorized total human knee prosthesis. *Measurement Science and Technology, 25*(2), 025702. https://doi.org/10.1088/0957-0233/25/2/025702.
215. Zhang, Q., Wang, Y., & Kim, E. S. (2014). Power generation from human body motion through magnet and coil arrays with magnetic spring. *Journal of Applied Physics, 115*(6), 064908. https://doi.org/10.1063/1.4865792.
216. Brunner, S., Gerst, M., & Pylatiuk, C. (2017). Design of a body energy harvesting system for the upper extremity. *Current Directions in Biomedical Engineering*. https://doi.org/10.1515/cdbme-2017-0067.
217. Bendame, M., Abdel-Rahman, E., & Soliman, M. (2015). Electromagnetic impact vibration energy harvesters. In M. Belhaq (Ed.), *Structural nonlinear dynamics and diagnosis* (Vol. 168, pp. 29–58). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-19851-4_2.
218. Geisler, M., Boisseau, S., Perez, M., Ait-Ali, I., & Perraud, S. (2016). Scaling effects in a non-linear electromagnetic energy harvester for wearable sensors. *Journal of Physics:*

Conference Series, 773, 012044. https://doi.org/10.1088/1742-6596/773/1/012044.
219. Ning, C., Tian, L., Zhao, X., Xiang, S., Tang, Y., Liang, E., et al. (2018). Washable textile-structured single-electrode triboelectric nanogenerator for self-powered wearable electronics. *Journal of Materials Chemistry A, 6*(39), 19143–19150. https://doi.org/10.1039/C8TA07784C.
220. Zhang, Z., Du, K., Chen, X., Xue, C., & Wang, K. (2018). An air-cushion triboelectric nanogenerator integrated with stretchable electrode for human-motion energy harvesting and monitoring. *Nano Energy, 53,* 108–115. https://doi.org/10.1016/j.nanoen.2018.08.011.
221. Tang, W., Jiang, T., Fan, F. R., Yu, A. F., Zhang, C., Cao, X., et al. (2015). Liquid–metal electrode for high-performance triboelectric nanogenerator at an instantaneous energy conversion efficiency of 70.6%. *Advanced Functional Materials, 25*(24), 3718–3725. https://doi.org/10.1002/adfm.201501331.
222. Dai, D., & Liu, J. (2014). Hip-mounted electromagnetic generator to harvest energy from human motion. *Frontiers in Energy, 8*(2), 173–181. https://doi.org/10.1007/s11708-014-0301-2.
223. Xia, K., Zhu, Z., Zhang, H., Du, C., Fu, J., & Xu, Z. (2019). Milk-based triboelectric nanogenerator on paper for harvesting energy from human body motion. *Nano Energy, 56,* 400–410. https://doi.org/10.1016/j.nanoen.2018.11.071.
224. Huang, T., Wang, C., Yu, H., Wang, H., Zhang, Q., & Zhu, M. (2015). Human walking-driven wearable all-fiber triboelectric nanogenerator containing electrospun polyvinylidene fluoride piezoelectric nanofibers. *Nano Energy, 14,* 226–235. https://doi.org/10.1016/j.nanoen.2015.01.038.
225. El-Sayed, A.-R., Tai, K., Biglarbegian, M., & Mahmud, S. (2016). A survey on recent energy harvesting mechanisms. In *2016 IEEE Canadian conference on electrical and computer engineering* (*CCECE*) (pp. 1–5). IEEE.
226. Khan, F. U., & Qadir, M. U. (2016). State-of-the-art in vibration-based electrostatic energy harvesting. *Journal of Micromechanics and Microengineering, 26*(10), 103001.
227. Lu, Y., Cottone, F., Boisseau, S., Marty, F., Galayko, D., & Basset, P. (2015). A nonlinear MEMS electrostatic kinetic energy harvester for human-powered biomedical devices. *Applied Physics Letters, 107*(25), 253902.
228. Zhang, Y., Wang, T., Luo, A., Hu, Y., Li, X., & Wang, F. (2018). Micro electrostatic energy harvester with both broad bandwidth and high normalized power density. *Applied Energy, 212,* 362–371.
229. Bu, L., Wu, X., Wang, X., & Liu, L. (2013). Liquid encapsulated electrostatic energy harvester for low-frequency vibrations. *Journal of Intelligent Material Systems and Structures, 24*(1), 61–69.
230. Leonov, V. (2011). Thermoelectric energy harvester on the heated human machine. *Journal of Micromechanics and Microengineering, 21*(12), 125013.
231. Sultana, A., Alam, M. M., Middya, T. R., & Mandal, D. (2018). A pyroelectric generator as a self-powered temperature sensor for sustainable thermal energy harvesting from waste heat and human body heat. *Applied Energy, 221,* 299–307.
232. Kim, C. S., Yang, H. M., Lee, J., Lee, G. S., Choi, H., Kim, Y. J., et al. (2018). Self-powered wearable electrocardiography using a wearable thermoelectric power generator. *ACS Energy Letters, 3*(3), 501–507. https://doi.org/10.1021/acsenergylett.7b01237.
233. Du, Y., Cai, K., Chen, S., Wang, H., Shen, S. Z., Donelson, R., et al. (2015). Thermoelectric fabrics: Toward power generating clothing. *Scientific Reports, 5,* 6411.
234. Leonov, V. (2013). Thermoelectric energy harvesting of human body heat for wearable sensors. *IEEE Sensors Journal, 13*(6), 2284–2291.
235. Bowen, C. R., Taylor, J., LeBoulbar, E., Zabek, D., Chauhan, A., & Vaish, R. (2014). Pyroelectric materials and devices for energy harvesting applications. *Energy and Environmental Science, 7*(12), 3836–3856.

Salman Khalid received his B.S. Mechanical Engineering degree in 2012 and M.S. Mechanical Engineering degree in 2016 from NUST, Pakistan. Currently, he is a PhD scholar in Department of Mechanical Engineering, Dongguk University, Seoul, Korea. His research interests include the Smart materials, Mechanics of Composite materials and Structural Health Monitoring by using machine learning and deep learning techniques.

Izaz Raouf received his B.S. degree in Mechanical Engineering from UET Peshawar, Pakistan in 2017. Currently he is a Masters student in Department of Mechanical Engineering, Dongguk University, Seoul, Korea. His research interests include the Finite Element Modeling of hyperthermia, Heat Transfer and Smart Materials.

Asif Khan received his B.S. degree in Mechanical Engineering from UET Peshawar, Pakistan, in 2011, and M.S leading to PhD degree in Mechanical Engineering from the Department of Mechanical Engineering, Dongguk University, Seoul, South Korea, in 2018. Dr. Khan is now working as a research professor in the Department of Mechanical Engineering, Dongguk University. His main research interests are mechanics of smart composite laminates, machine leaning and deep learning for structural health monitoring, applications of smart materials, Energy Harvesting form ambient resources, and modeling and simulation of dynamic behavior of engineering systems.

Nayeon Kim received her B.S. degree from the Department of Mechanical, Robotics and Energy Engineering, Dongguk University, Seoul, South Korea, in 2018. She is now pursuing her M.S. degree in the Department of Mechanical, Robotics and Energy Engineering, Dongguk University. Her main research interests are smart materials, structures and deep learning.

Heung Soo Kim received his B.S. and M.S. degrees in the Department of Aerospace Engineering from Inha University, Korea in 1997 and 1999, respectively. He got his Ph. D degree in the Department of Mechanical and Aerospace Engineering from Arizona State University in 2003. He is now working as a professor in the Department of Mechanical, Robotics and Energy Engineering, Dongguk University. His main research interests are smart materials and structures as applied to aerospace structures and vehicles.