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REVIEW

Piezoelectric energy harvesting for self-powered wearable upper limb applications

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Abstract

Wearable devices can be used for monitoring vital physical and physiological signs remotely, as well as for interacting with computers. Widespread adoption of wearables is somewhat hindered by the duration time they can be used without re-recharging. To ensure uninterrupted operation, these devices need a constant and battery-less energy supply. Scavenging energy from the wearable's surroundings is, therefore, an essential step towards achieving genuinely autonomous and self-powered devices. While energy harvesting technologies may not completely eliminate the battery storage unit, they can ensure a maximum duration of use. Piezoelectric energy harvesting is a promising and efficient technique to generate electricity for powering wearable devices in response to body movements. Consequently, we systematically survey the range of technologies used for scavenging energy from the human body, with a particular focus on the upper-limb area. According to our review and in comparison to other upper limb locations, highest power densities can be achieved from piezoelectric transducers located on the wrist. For short and fast battery charging needs, we therefore review the range of materials, architectures and devices used to scavenge energy from these upper-limb areas. We provide comparisons as well as recommendations and possible future directions for harvesting energy using this promising technique.

KEYWORDS
piezoelectric energy harvesting, upper limbs, wearable devices

1 | INTRODUCTION

Wearable electronic devices have attracted plenty of interest in health monitoring applications.[1–5] Such devices emerged in the 1990s, and aimed to provide users with the ability to manage their own health and to interact with their healthcare providers.[6] However, to ensure uninterrupted monitoring, a sustainable and continuous power supply is required for sensing, transmitting and analyzing data.[7] Chemical-cell batteries have commonly been used to fulfil the power demands of wearable devices, but their periodical replacement or recharging hinders their widespread adoption.

Scavenging energy from the human body and its surroundings to power wearable electronic devices has been successfully demonstrated in the literature. Examples of energy sources include kinetic energy,[8–13] light,[14,15] temperature[16,17] and radio frequency.[18] These energy harvesting techniques can be used standalone or in conjunction with batteries.[19–21] For instance, harvesting energy from light can be achieved using flexible photovoltaic cells to power a wearable bracelet for electromyogram (EMG) gesture recognition. The lifetime of the wristband was extended to over 500 hours with a single 200 mAh battery.[22] Despite current interests in predicting the amount of harvestable energy from intermittent sources such as the sun, photovoltaic energy harvesting is strongly dependent on the incoming light intensity.[23,24] Solar cells can provide high and stable energy densities when exposed to outdoor sunlight (around 15 mW cm^{-2}). However, this power density immediately drops to below 10 μW cm^{-2} at indoor conditions, which may not sufficiently meet the needs of modern wearable devices.[25]

Other technologies for powering smart bracelets included the use of wearable thermoelectric generators (TEGs), which converted human heat to 280 μW of power.[16] Based on the Seeback effect, TEGs generate electricity from body heat. Therefore, the output power of TEGs is highly dependent on the body location, the environmental conditions, as well as the activity and general clothing of its wearer.[17] Naturally, the amount thermo-generated power is strongly dependent on the temperature difference between the TEG and the human body.[26]

Unlike solar or thermal energy sources, kinetic energy harvesting is neither location nor time dependent. Kinetic energy harvesters are typically inertial spring-mass systems. Electrical energy is scavenged using one or a combination of different transduction mechanisms. The main transduction mechanisms are triboelectric, electromagnetic, electrostatic and piezoelectric.[27,28] We will discuss each of these transduction mechanisms in the text below.

First, triboelectrification is a term used to describe the combined effect of contact electrification and electrostatic induction.[29] When two layers are in contact and make friction with one another, induced electrical charges appear on the surfaces due to contact rubbing motions. These motions include sliding movement, vertical touching and torsional stress. After separating the layers, some charges tend to lose electrons, while others retain excess electrons, which may generate triboelectric charges on the material's surface. These triboelectric charges produce an electrostatic field that causes electrons to flow from an external circuit.[30,31] Based on this effect, Wang et al. proposed the triboelectric nanogenerator (TENG) in 2012.[32] Since then, TENGs have experienced a surge in research interest due to their unique and promising approach for energy harvesting.[33,34] For example, Zhang et al. demonstrated a printed silk-fibroin-base TENG that achieved an output voltage of 666 V and a power density of 412 μW cm^{-2}.[35] However, since TENGs are in their early stages of research, there are ongoing research activities in optimising their durability, stability and efficiency using a range of materials, architectures and power management techniques.[31]

On the other hand, electromagnetic generators are based on Faraday's law of electromagnetic induction, whereby a potential difference is induced when an electric conductor moves through a magnetic field.[36] These electromagnetic energy harvesters usually produce high output power from human motion, but their bulky and mechanical nature may cause wearer discomfort.[37] In fact, the output power of electromagnetic devices is usually dependent on the number of coils and magnetic mass. Hence, it is a challenge to reduce the size, weight and complexity of these energy harvesters.[29] For example, a frequency up-converted electromagnetic energy harvester was demonstrated by Halim et al. to scavenge energy from the human limbs. They demonstrated an average power density of 0.33 mW cm^{-3} via low-frequency human vibration.[38]

The electrostatic transduction mechanism is mainly achieved via a varying capacitance. Here, the capacitor needs to be initially charged by an external voltage source, or make use of pre-charged electret materials.[39] Despite good compatibility with integrated circuit and microelectromechanical system (MEMS) technologies, the power densities currently achieved using electrostatic energy harvesters are low.[40,41] For instance, an electrostatic energy harvester consisting of two plates was fabricated using advanced MEMS technology in 2018 by Zhang et al., which delivered a maximum power output of 4.95 μW for an active volume of 0.19 cm^3.[42]

Compared with other transduction mechanisms, piezoelectric materials have the ability to directly convert changes in human motion into electrical signals without any further external input.[43] Hence, the architecture of piezoelectric energy harvesters is simple, which is particularly advantageous in small scale wearable devices. Moreover, piezoelectric energy harvesters are sensitive to small displacements, and the reported output voltage and power densities are higher in practical applications.[27,44–46]

For health monitoring and physical rehabilitation applications that are based on electrocardiogram (ECG) or electromyogram (EMG) signal processing, a sustainable power supply is indispensable.[47,48] Most piezoelectric energy harvesting systems were designed to scavenge energy from

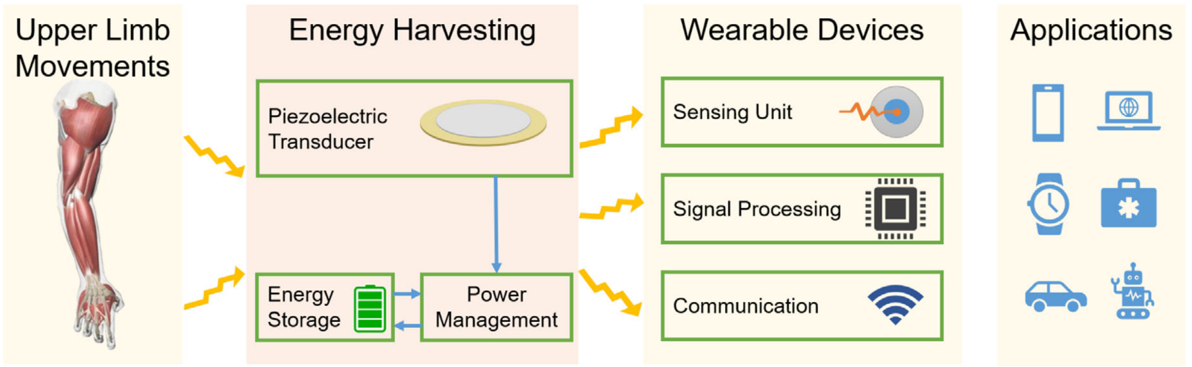

FIGURE 1 Building block of a typical wearable device

the lower body.[49–51] However, we believe that the upper limb is an attractive location for short and fast battery charging needs. For example, the upper limbs are involved in many small and frequent daily activities that are often overlooked such as housekeeping, playing instruments and even working with computers. These overlooked movements can now be used to power wearable devices. Moreover, the upper limbs are located close to internal organs that need constant monitoring. Therefore, there is less likelihood of energy being wasted until it reaches health monitoring devices such as ECGs and EMGs.[52]

To start, the building block of typical wearable devices is provided in Section 2. Section 3 introduces our research methodology in collecting and synthesizing evidence. Section 4 explains the basic mathematical modelling of piezoelectric energy harvesters. Next, the recent development of piezoelectric generators in different parts of the human body is discussed in Section 5, and piezoelectric transducers in the upper limb region are mainly discussed in Section 6. Finally, Section 7 provides concluding remarks as well as key findings and recommendations for future developments.

2 | BASIC BUILDING BLOCKS OF A SELF-POWERED WEARABLE DEVICE

Device designs in most wearables involve bulky on board power sources, direct physical connections and high powered sensors, which drastically limit their practical application.[53] Similar to other kinetic energy harvesters, piezoelectric energy harvesters rely on converting vibration energy into useful electrical signals from the human motions, which is beneficial for powering on-body health monitoring devices. In this section, the main building blocks and typical power requirements of wearable devices are provided.

Figure 1 demonstrates the main building blocks of a wearable device, which makes use of the piezoelectric energy harvesting technique. The energy harvesting unit converts mechanical energy into electrical energy via a piezoelectric transducer. The collected energy could either be used directly or stored in a reservoir, such as a lithium-ion battery or a supercapacitor. The sensing unit is responsible for acquiring data from the wearable's environment, which is then processed in the signal processing unit. As demonstrated from the figure, all these units can be powered using energy scavenged by the piezoelectric energy harvester. The focus of our review is on this energy harvesting block, where piezoelectric transducers are used for converting or scavenging energy from human kinetic movement.

TABLE 1 Power consumption for a commercial wearable device

Component	Description	Power consumption/W
Signal processing	Micro-controller unit	250 μW
	Conditioning circuit	37 μW
	ADC	16.1 μW
Wireless communication	Radio frequency identification (RFID)	25-63 mW
	Low power Bluetooth	13.86-15.642 mW
	Low power Wi-Fi	2.5-809 mW
	ZigBee	52.22 mW

According to our survey, we recognized that greatest power consumption in a typical wearable application occurs in the communications module, as demonstrated from Table 1.[54,55] Currently, power consumption in the signal processing unit has been reduced to below 100 μW, whereas power consumption in the wireless communication unit has been reduced to 3.2 mW.[56]

Critical medical applications require continuous monitoring without any loss of power. Therefore, storage is important. Energy storage ensures that an appropriate amount of power and voltage are fed to the wearable's building blocks, which are shown in Figure 1. Herein, batteries have typically been used in wearable devices. In that case, battery lifetime becomes a critical issue and is heavily dependent on a number of important usage factors, which include temperature, number of cycles and depth of discharge (DOD).[57,58] Moreover, battery technologies respond to these usage effects in different ways. For example, at room temperature, lithium-ion (Li-ion) batteries, which have been used in wearable electronics since the 1950s, have cycle lifetimes of 550 at 100% DOD and 1000 at 50% DOD.[59] In comparison, these batteries will need to be replaced more often than a wearable device using nickel-metal hydride (NiMH) batteries, which have cycle lifetimes of 1200 at 100% DOD and 1900 at 50% DOD.[60] It is noteworthy to mention that frequent battery charging or eventual replacement will affect user experience and may hinder the market penetration of wearable devices. Consequently, novel energy harvesting techniques that rely on converting energy from body movements are needed to overcome these limitations. Currently, piezoelectric energy harvesters that generate 330 μW cm$-^{3}$ power densities from the human body can now be used to extend battery lifetime.[25] We will discuss these technologies in the subsequent sections.

3 | METHODOLOGY

In this section, we define our research methodology in collecting and synthesizing evidence on piezoelectric energy harvesting using clearly defined criteria. We describe the piezoelectric energy harvesting technologies used for different parts of the human body, with a focus on the upper limb. Novel materials and structures are discussed, as well as their advantages and disadvantages.

Similar to the methodology described in,[61] we first defined the inclusion criteria of our search. Second, we selected the relevant literature that met these criteria. Third, we analyzed and interpreted our search results. In this case, we defined the following inclusion criteria (InC):

InC1: Literature available in English.

InC2: Literature related to piezoelectric energy harvesting.

InC3: Literature related to the upper limb.

InC4: Literature reporting the amount of harvestable power or energy.

Having defined our inclusion criteria, we defined our approach in searching for piezoelectric energy harvesting technologies for upper limb applications. We used "Google Scholar" and "Web of Science" for our search using the descriptors in Table 2.

TABLE 2 Descriptors used in our systematic literature review

Descriptor	Definition	Synonyms
Energy harvesting	Energy harvesting is the process by which energy is derived or scavenged from external sources.	Energy scavenging
Piezoelectricity	The phenomenon of converting mechanical energy to electrical energy in crystalline or semi-crystalline materials.	None
Upper limb	The upper limb is the region extending from the deltoid region to the hand.	Upper extremity

Finally, we developed search strings using Boolean operators (AND, OR) to connect these descriptors. We discarded any literature that did not meet these inclusion criteria. For example, literature that did not mention the amount of power or energy (or a combination of voltage and current) harvested were not included in our literature review.

4 | MATHEMATICAL MODELLING OF PIEZOELECTRIC ENERGY HARVESTERS

4.1 | Piezoelectric effect

Mechanical energy is one of the most omnipresent energy sources from ambience and human body. It is available in the form of human movement, breathing, heartbeat, blood pressure and vibrations. Piezoelectric power harvesting is the popular strategy to convert mechanical energy to electrical energy. The direct piezoelectric effect is the ability of certain crystalline materials to develop an electric charge proportional to the mechanical stress, which was first discovered in quartz by Pierre and Jacques Curie in 1880.[62] Equation 1 shows the basic principle of the direct piezoelectric effect that is suitable for power harvesting.

$$\mathrm{D}_{i} = \mathrm{d}_{ij} \cdot \mathrm{T}_{j} + \varepsilon^{T}_{ik} \cdot \mathrm{E}_{k} \tag{1}$$

Where D is the electric displacement, T_j is the stress tensor, E_k is the electric field, ε^{T}_{ik} is the dielectric permittivity under a zero or constant stress, d_{ij} is the direct piezoelectric charge coefficient.[63] Where i and k varies from 1 to 3, and j varies from 1 to 6. The detailed constitutive matrix is

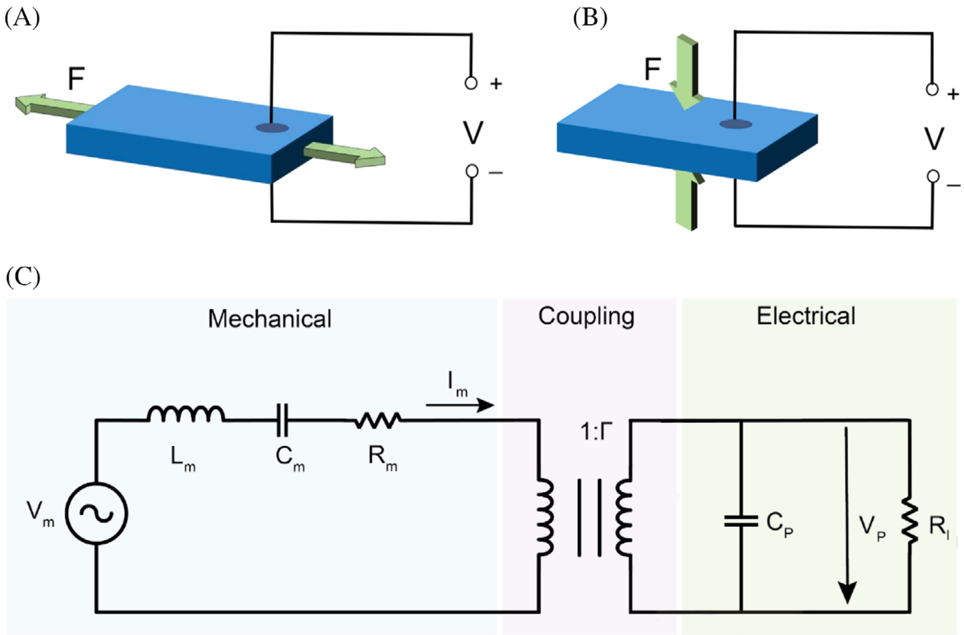

FIGURE 2 Piezoelectric material operated in (A) 31 mode, and (B) 33 mode. C, Electromechanical equivalent circuit of the piezoelectric energy harvester

described in Equation 2.

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11}^T & \varepsilon_{12}^T & \varepsilon_{13}^T \\ \varepsilon_{21}^T & \varepsilon_{22}^T & \varepsilon_{23}^T \\ \varepsilon_{31}^T & \varepsilon_{32}^T & \varepsilon_{33}^T \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{2}$$

Where subscripts 1, 2 and 3 present x, y and z directions in the Cartesian coordinate system, and subscripts 4, 5, and 6 indicate the rotational stress and strains along the x, y, and z directions. There are two general modes 33 and 31 of piezoelectric materials in power harvesting applications. The first number (3) means the voltage generated along the Z-axis for both modes. The electrodes are attached on the top and bottom side of the piezoelectric material. The second number indicates the direction of the applied force. In 33 mode, the applied pressure is the same direction with the generated voltage, while 31 mode shows the force is applied along the x-axis (see Figure 2A,B).

4.2 | Figure of merit

According to the literature,[64] there are three major steps associated with piezoelectric energy harvesting in an electromechanical system:

(i) Mechanical-mechanical energy transfer, which includes the mechanical stability and mechanical impedance matching.
(ii) Mechanical-electrical energy transfer, which includes electromechanical coupling in a piezoelectric element. The electromechanical coupling is an important factor, where the high coupling means a large amount of mechanical energy can be converted into useful electricity.
(iii) Electrical-electrical energy transfer, which includes electrical impedance matching. For instance, in the presence of a DC/DC converter to accumulate energy into an electrical rechargeable battery.

At the second phase, part of the mechanical energy through the piezoelectric transducer is converted into electrical energy due to electromechanical coupling. The induced voltage in this transducer can be determined using:

$$V = \frac{gFt}{A} \tag{3}$$

Where g is the piezoelectric voltage constant, F is the applied force, t is the thickness of the piezoelectric transducer, and A is the area of the surface.[65] Subsequently, the piezoelectric charge constant can be calculated using:

$$d = \frac{CV}{F} \tag{4}$$

For example, in 33 mode, the output electric power can be determined using:

$$P = \frac{1}{2}CV^2 \cdot f$$
$$= \frac{1}{2} \cdot g_{33} \cdot d_{33} \cdot F^2 \cdot \frac{t}{A} \cdot f \tag{5}$$

where the product of g and d is the "figure of merit". Due to $(Q_{33})^2 = d_{33}\ g_{33}$, then electrical energy generated in the piezoelectric transducer can be presented as:

$$W = \frac{(Q_{33})^2 F^2 t}{2A} \tag{6}$$

4.3 | Equivalent circuit

From an electrical perspective, a piezoelectric transducer can be represented using the small signal equivalent circuit shown in Figure 2C. Here, figure shows the generalized lumped element modelling of a piezoelectric generator. The left part of the figure is the mechanical domain, where the voltage source V_m simulates an alternating input force. Similarly, the inductor, L_m, represents the mass, the capacitor, C_m, donates the stiffness of the piezoelectric beam and the resistor, R_m, is the parasitic damping. On the right side of the figure, the piezoelectric output capacitance is indicated by C_p, the output voltage across the piezoelectric terminal is denoted by V_p, and the external load is represented by R_l. In addition, a transformer of a winding ratio of 1: Γ has been used to couple the mechanical domain to the electrical domain, where Γ denotes the generalized electromechanical coupling factor. Accordingly, the output voltage across the load resistance can be determined from:

$$V_P = \frac{1}{\Gamma}\left(V_{m-}L_m\dot{I}_m - R_m I_m - \frac{1}{C_m}\int I_m \mathrm{d}t\right) \tag{7}$$

Thus, the output power is given by:

$$P = \frac{V_p^2}{R_l} \tag{8}$$

5 | SUMMARY OF PIEZO-ENERGY HARVESTING TECHNIQUES FROM THE HUMAN BODY

The aim of this section is to briefly review the range of motion energy harvesting techniques from the human body using piezoelectric transducers. There are two kinds of mechanical energy can be scavenged from the human body. The first is related to continuous activities, such as breathing and heart beating; while the other is related to discontinuous movements, such as walking and joint movements.[66]

Among these, the process of walking produces the largest amount of power compared with other body motions. According to the literature, a 68 kg man is able to generate around 67 W when walking at a speed of two steps per second.[67] To scavenge energy from human gait, Starner et al. first proposed using piezoelectric shoe inserts in 1996.[67] Subsequently, Shenck and Paradiso from MIT Media Laboratory improved the concept in 2001.[68] They designed two different insoles based on a flexible polyvinylidene fluoride (PVDF) bimorph stave and a semiflexible lead zirconate titanate (PZT) dimorph. Energy from these insoles can activate a radio frequency (RF) tag that transmitted a short-range wireless identification code while walking. Subsequently, various designs have been developed to improve the performance of piezoelectric energy harvesting from shoes. In 2012, a shoe insole pedometer consisting of PVDF rolls and a 2 V organic pedometer circuit was a first step towards achieving flexible large-area energy harvesting.[69] More recently, a two-stage force-amplification compliant mechanism achieving an average output power of 11.0 mW and a peak output power of 31.7 mW were experimentally demonstrated at 1.0 Hz. [70]

Body joints are also attractive locations for power harvesting purposes due to their high motion amplitude, fast angular velocity, large impulse force and high frequency of use in daily human activities.[71] For example, the knee joint produces high biomechanical energy since it generates a larger torque in comparison to other human joints.[72] Knee joint motions are often related to gait motion, where walking and running frequencies are normally in the range of 0.5-5 Hz.[72–74] Therefore, the literature on knee energy harvesting focused on the collection of biomechanical energy generated during gait movement. For example, Pozzi et al. demonstrated a plucking-based frequency up-conversion harvester, which was based on scavenging rotational energy from the knee during normal gait achieved an output power of 17 mW.[75,76]

Another piezoelectric energy harvesting device that successfully generated electrical power from knee motion during human gait was demonstrated by Beyaz.[77] This consisted of two MEMS-based piezoelectric patch transducers, which were optimized for placement around knee joints with minimal footprint.[77] During walking and running, the maximum output power was 6.2 µW and 12 µW. The amount of power generated during these experiments showed the promising potential of this device as an independent onboard power component, and as a continuous battery charger for wearable electronic devices.

Even for relatively minor activities such as eye blinking, piezoelectric transducers have effectively been used to convert motional energy into electricity. For example, a self-powered sensor was developed for both energy harvesting and health rehabilitation monitoring, which was based on polymeric piezoelectric nano/microfibers.[78] The physical structure of the self-sustained cantilever consisted of 500 PVDF nanofibers deposited on a flexible polyvinyl chloride (PVC) substrate through the near-field electrospinning technique. To firmly connect the PVDF nanofibers with copper foil tape electrodes, silver paste was used on both the substrate and the interconnects, before finally being encapsulated by polydimethylsiloxane (PDMS). The device was attached in the vicinity of the eye and demonstrated high sensitivity. The generated output voltage and current due to skin wrinkling during eye blinking was 0.2 V and 40 nA.

Furthermore, continuous energy can be harvested from the process of human breathing. There are two kinds of energy that can be collected in this case. The first relies on scavenging energy due to the intake and release of air, which can produce approximately 1 W of power. The other relies on chest expansion, which requires a tight band fixed around the chest of the user to generate around 0.83 W when breathing normally.[67] Further practical demonstrations are available in the literature. For example, a flexible yarn-based piezoelectric nanogenerator was developed as a self-powered breathing sensor to detect human inhalation/exhalation. The breathing motion was also used to power five commercial LEDs and a display device.[79] The device was fabricated via a layer-by-layer brush-coating technique which consisted of the following parts from inside to outside: a flexible yarn layer, an inner Ag electrode, a BiTO nanoparticles layer, the PVDF polymer matrix, an outer Ag electrode and a PDMS packaging layer. The device generated a maximum peak-to-peak open-circuit voltage, short-circuit current and power density of 60 V, 400 nA and 18.5 mW m^{-2} under 1 N periodic force.

Moreover, a smart mask was designed based on a flexible self-powered breathing sensor, which generated 6 V (peak-to-peak) during human breathing from the mouth. A composite piezoelectric rubber band was designed and fabricated to harvest energy from circumferential stretching during breathing.[80] PTFE films were deposited inside the cellular PDMS structures, and stretchable gold electrodes were covered on both sides, before charges were injected internally under a strong electric field. Thus, more than 20 μC of electric charge could be collected per breath when the rubber band was mounted around chest.

For harvesting energy from blood pressure, a wave-shaped composite piezoelectric generator composed of P(VDF-TrFE) film and Metglas has been proposed.[81] The P(VDF-TrFE)/Metglas composite was first formed into a membrane and cut into several equal narrow strips. Next, semi-cylinders were inserted into the composite layer to construct a wave structure. Finally, the structure was encapsulated with PDMS after which the semi-cylinders were removed, after curing. The wave-configuration provided a pre-stretch in P(VDF-TrFE) film, and where Metglas and PDMS polymer could undergo rapid shape recovery. Due to this pre-stretch, the composite not only generated compressive stress on the piezoelectric layer but also changed the curvature and stress profile along the length direction. The combination of d33 and d31 parameters significantly enhanced the piezoelectric performance of the wave-shaped structure. The wave-shaped generator was sensitive to variations in blood pressure, where the detection of a clear pulse signal was enabled, particularly beneficial for human health monitoring when placed on the wrist.

In addition to the piezoelectric generations we mentioned above, as shown in Figure 3, more research has been devoted towards the development of piezoelectric energy harvesters from the upper limb area. Therefore, in the next section we will focus on reviewing these technologies in detail.

6 | ENERGY HARVESTING FROM THE UPPER LIMB

In this section, we will discuss the results from our search criteria. In total, 24 references satisfied our inclusion criteria. A total of nine references on piezoelectric energy harvesting did not mention the transducer volume and only reported the harvestable amount of power. We will discuss the latest developments in all 24 references in the following sections.

The phenomenon of piezoelectricity occurs in naturally occurring single crystals such as quartz (SiO_2), lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$). Moreover, it also occurs in polycrystalline ceramics such as barium titanate ($BaTiO_3$), PZT [Pb (Zr1–xTix) O_3)] and potassium niobate ($KNbO_3$)), polymers such as polyvinvylidene fluoride (PVDF), polylactic acid (PLA) and piezo-composites.

It is noteworthy to mention that the materials used during the fabrication of piezoelectric generators have evolved tremendously since World War II.[82] Desirable material properties and characteristics for wearable applications include high flexibility, high time stability, high insulation resistivity and low cost of production.[82] Ceramic materials today are more economical and can be fabricated for achieving high, consistent and reliable performance for a variety of applications. PZT is the most well-known piezoceramic material based on solid solutions of $PbZrO_3$ (PZ)

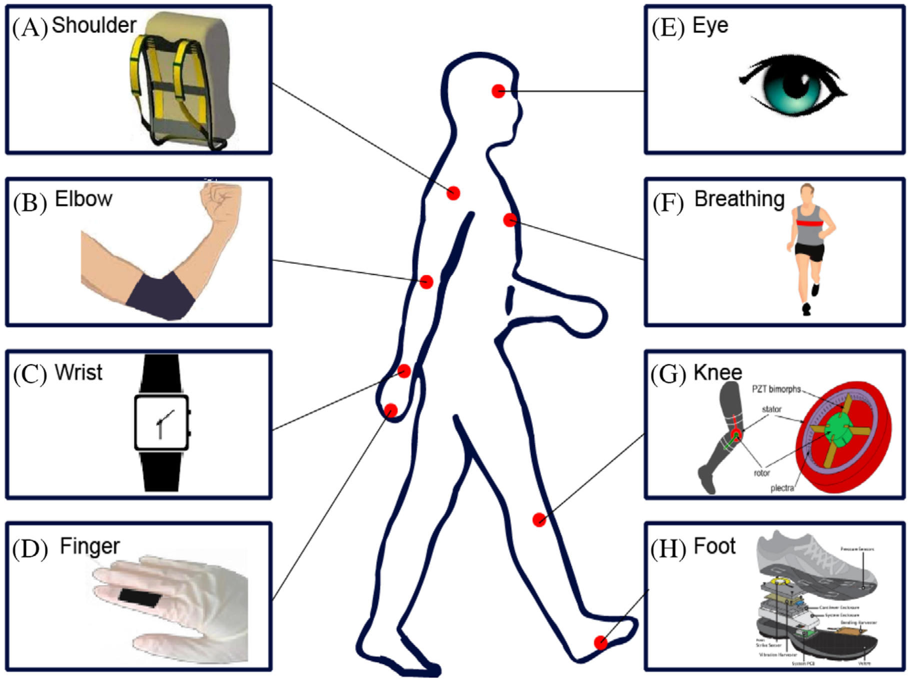

FIGURE 3 Various piezoelectric energy harvesting techniques from different locations on the human body including (A) The shoulder (reproduced with permission from[115]), (B) Elbows, (C) The wrist, (D) Fingers (reproduced with permission from[99]), (E) Eyes, (F) Chest, (G) Knees (reproduced with permission from[75]), and (H) Feet (reproduced with permission from[130])

and $PbTiO_3$ (PT).[82] Due to their excellent piezoelectric properties and wide commercial availability, PZT ceramics are preferred materials for harvesting kinetic energy from the human body.

Piezopolymers are also attracting plenty of interests due to their desirable properties in flexible piezoelectric generators. The typical commercial piezoelectric polymer of choice is PVDF, which was discovered by Kawai and Kureha in 1969.[62] PVDF is made from long chains of the repeating monomer (-CH_2 –CF_2–), and it has small permittivity, leading to a high piezoelectric voltage constant g.[83] The piezoelectric charge coefficient of poled PVDF thin film is 6–7 pC/N, which is higher than quartz crystals, but much lower than for PZT ceramics.[62,82] Due to their mechanical flexibility, it could be produced as a very thin film and attached to a curved structure. Additionally, PVDF sheets possess the ideal characteristics to be easily formed into the desired shape of a wearable device and are therefore suitable for pressure/stress sensor applications.[62]

Moreover, piezoelectric-based composites were first proposed in 1972.[62] The composite was made by hot rolling PZT powder and PVDF, which resulted in both high piezoelectricity and high flexibility. To combine the advantages of both constituent materials, the improvement method involved mixing the ceramic particles into the polymer. In order to obtain ideal piezoelectric properties for these composite materials, many researchers have investigated variations in parameters such as ceramic content and particle size, shape and configurations.

In this section, state-of-the-art piezoelectric generators for upper limb applications were presented. We also discussed and compared the performance of different materials applied in each of these upper limb locations. We will therefore focus on piezoelectric energy harvesting from four main parts of the upper limb. These are the hand, wrist, arm and shoulder. Moreover, according to their material composition, piezoelectric technologies can be divided into three main groups: ceramics, polymers and composites. In this case, the remainder of our analysis will focus on these areas.

6.1 | Hand

The human hand consists of four fingers, a thumb and a broad palm. The hand is one of the most flexible parts of the human body and performs a variety of sophisticated and complicated activities in daily life. However, harvesting energy from the hand is still challenging, since energy harvesters need to be highly flexible, small in size and avoid hindering finger movement. Therefore, in addition to improving the structure and architecture of these energy harvesters, research is also dedicated to developing novel

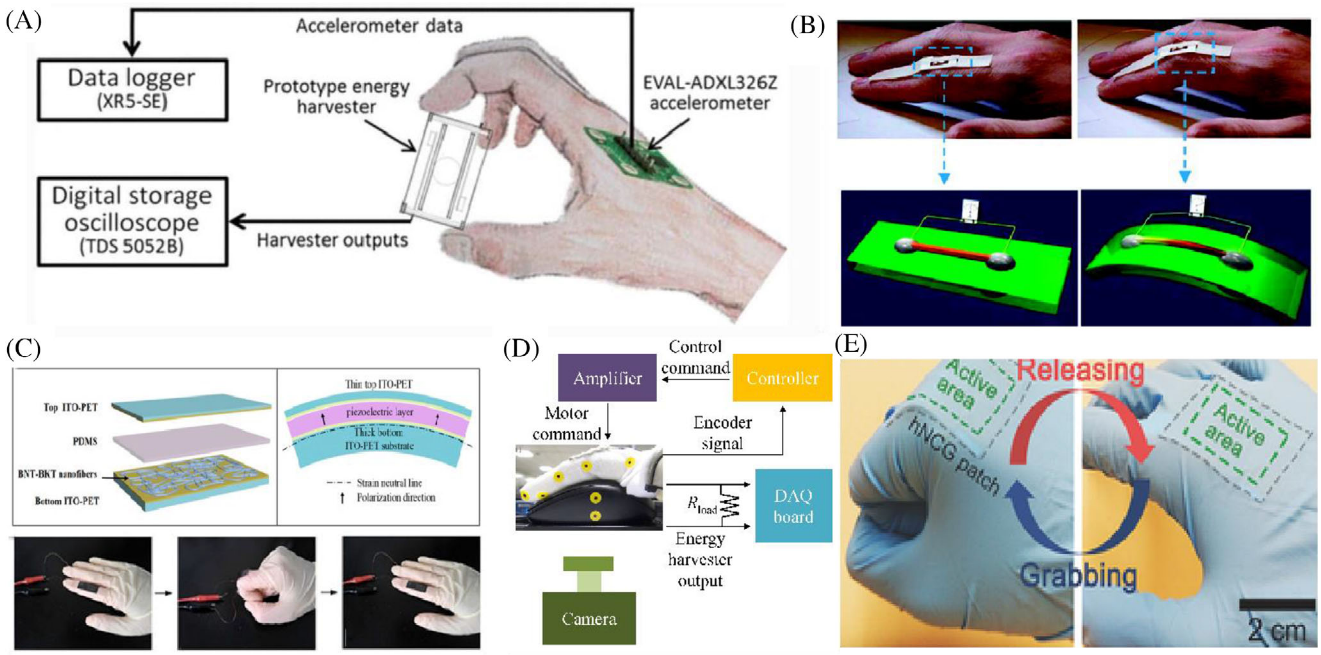

FIGURE 4 A, Schematic diagram of the handshaking vibration setup for the fabricated prototype energy harvester. Reproduced with permission from.[85] B, A single wire generator attached to a human index finger to produce power output by finger bending motions. Reproduced with permission from.[98] C, Composition of the BNT-BKT nanogenerator and its placement on the finger. Reproduced with permission from.[99] D, Experimental setup for a human finger to harvest energy from clicking motions. Reproduced with permission from.[100] E, Photographic images of the flexible lead-free perovskite nanowire piezopolymer attached on the back of a hand. Reproduced with permission
from[102]

materials to collect kinetic energy from hand movements. We shall discuss the latest developments in the following sections.

6.1.1 | Ceramics

Handshaking is a relatively high-amplitude and high-frequency activity compared with other hand movements. It therefore generates more kinetic energy and is more suitable for energy harvesting. A box-typed prototype of a harvester converting mechanical hand motions into electrical energy was first designed in 2009.[84] The basic configuration consisted of a frame with a track to guide a sliding free mass, with two piezoelectric bimorphs installed at both ends of the frame. When the frame was shaken along the direction of the track, a proportion of the kinetic energy accumulated by the mass encountering was converted into electrical energy. A more complex structure of power harvester device was proposed in 2018[85] with the similar configuration, which involved a sliding track containing a free metallic ball, as shown in Figure 4A. The device incorporated a flexible sidewall at each end of a cylindrical channel, with a mass-loaded unimorph type piezoelectric beam clamped on. When a handshaking action was performed, the metal ball impacted the sidewalls, thereby stimulating vibration of the piezoelectric beams. The average output power of the optimal load was 175 μW, and its power density was 7.6 μW cm^{-3}.

Although the box-typed harvester achieved a high power density, its large size may cause wearer discomfort. Therefore, lighter structures are required to maintain long-term wearer comfort. For example, flexible piezoelectric skin with pre-stressed structure (PSS) was demonstrated.[86] The specific structure could enhance the output generated voltage by the buckling effect and could attach the finger closely to harvest energy from low-frequency movement. This kind of artificial piezoelectric skin is based on the Aluminium Nitride (AlN) active layer, which is a piezoelectric ceramic with high thermal conductivity, high resistivity and high piezoelectric coefficient. So, it is a highly attractive material in piezoelectric microelectromechanical systems.[87,88] When a deformation was applied to a PSS, a fast transition generated huge variation in total elastic energy, which resulted in higher output voltage. The PSS device was mounted to a flexible glove to follow the deformation during the finger folding and unfolding states. Experimental results demonstrated the output voltage was 0.7 V and the estimated power density was 0.4 mW cm^{-3}.

Furthermore, piezoelectric nanogenerators have recently attracted research interest,[89–91] thanks to the efforts of Wang and Song[92] in 2006. They demonstrated the use of ZnO nanowire arrays to convert nanoscale mechanical energy into electrical energy, which opened new routes towards achieving flexible and miniaturized energy harvesters.

Therefore, ZnO nanowires are now the most widely used material for this purpose, due to its stability, cost-effectiveness, as well as its outstanding semiconducting and piezoelectric properties.[93] Consequently, researchers are currently investigating the use of ZnO nanowires for wearable piezoelectric nanogenerators.[94–96] For example, a new ZnO patterned-textile nanogenerator was demonstrated by Zhang et al., where ZnO nanorod arrays were vertically arranged between two layers of silver (Ag) coated nylon fabrics.[97] For the electrodes, silver paste was deposited on nylon fabrics via a screen-printing method. When attached on the human fingers and palms, this nanogenerator achieved output voltages and currents of 4 V, 20 nA for palm clapping, as well as 0.8 V, 5 nA for finger bending.

In another study, ZnO nanowires fixed laterally on both ends of flexible polyimide film formed a single wire generator.[98] When attached, repeated bending movements on the single nanogenerator located on the top side of the index finger resulted in a cyclical strain on the ZnO nanowire, which produced a piezoelectric potential within the wire and electric power output (Figure 4B). Periodic bending of the finger generated an output voltage of up to 25 mV, and the output current was measured to exceed 150 pA from a single nanogenerator.

The (Na0.83K0.17)0.5Bi0.5TiO_3 (BNT-BKT) nanofibers were used to fabricate the flexible piezoelectric nanogenerator for harvesting mechanical energy from finger movement.[99] The BNT-BKT nanofibers were produced via a combination of electrospinning and calcining processes. The nanofibers, under a PDMS layer, were sandwiched between two indium tin oxide-coated polyethylene terephthalate (ITO-PET) films to form a flexible nanogenerator (Figure 4C). When the BNT-BKT nanofiber-based generator was fixed on the finger, it was able to produce an output voltage of 0.49 V and current of 13.5 nA.

6.1.2 | Polymer

Compared with piezoceramics, which are hard and fragile, polymers are more suitable for generating energy from fingers. An energy harvesting system using flexible piezopolymer to scavenge finger motions was proposed by Cha et al. in.[100] The subject wore a glove with a pocket on the index finger that embedded a unimorph beam consisting of a PVDF piezoelectric film and a mylar substrate (Figure 4D). The moving displacement and frequency for mouse click motions of the human finger were under 1° and 2-3 Hz. The harvested energy from the human finger was around 1 nJ.

6.1.3 | Composite

Piezoelectric nanocomposite-based nanogenerator has gained more attention in wearable applications. For example, a hybrid composite nanogenerator was used to drive a self-powered microwire-based pH sensor.[101] The organic-inorganic hybrid composite was fabricated using ZnO nanowire and PVDF by solution-casting technique. To demonstrate the prospect of harvesting biomechanical energy, the hybrid nanogenerator was tested via the folding and pressing of fingers. The output voltage and current were 0.33 V, 0.062 μA and 1.3 V, 0.177 μA, respectively.

Moreover, a study focused on $BaTiO_3$ nanowires through a comparably simple hydrothermal method embedded into a P(VDF-TrFE) matrix, forming a piezoelectric-hybrid nanocomposite.[102] The ability of the nanogenerator to harvest energy from human activities was then examined, by attaching a patch-design device on the back of the hand, see Figure 4E. The maximum output voltage and current were approximately 8 V and 900 nA, respectively, for grabbing and releasing motions. The composite film combined the advantages of both ceramics and polymers, exhibiting higher piezoelectric potential and inducing larger local deformation.

The output power of an energy harvester is strongly dependent on device volume. Therefore, the performance of energy harvesters is compared in terms of their power density. In Table 3 we provide a comparison between different materials and structures for piezoelectric energy harvesting from the hand. In fact, power densities ranging from 0.32 to 400 μW cm^{-3} have been demonstrated. Although traditional ceramic materials (PZT) yield high output power for handshaking movements, their large and heavy nature is inconvenient for health monitoring applications. Therefore, piezocomposite materials are recommended for harvesting energy from hand motions, since they demonstrate both high power density (102.9 μW cm^{-3}) and flexibility.

6.2 | Wrist

The human wrist is involved in plenty of high amplitude movements with varying degrees of rotation. Moreover, people are accustomed to wearing accessories on their wrists, such as watches and bracelets. This makes it more acceptable for people to wear energy harvesting wristbands. Furthermore, in comparison to the hand, the wrist provides more space device implementation.

TABLE 3 Comparison between different materials and structures for piezoelectric energy harvesting from the hand

Material	Structure	Output voltage	Output power	Power density	Place	Motion	Size	Ref
Ceramics								
PZT	Sliding track	40 V	600 μW	10 μW cm^{-3}	Hand	Scratching	25 cm^3	[84]
PZT	Sliding track	5.05 V	175 μW	7.6 μW cm^{-3}	Hand	Hand shaking	23 cm^3	[85]
AlN	Stacked	0.7 V	0.2 μW	400 μW cm^{-3}	Finger	Bending	$0.4 \times 0.6 \times 0.0027$ cm^3	[86]
ZnO nanorod	Film	4 - 8V	40 - 80 nW	——	Hand	Palm clapping, finger bending	5 cm × 5 cm	[97]
ZnO nanowire	Film	25 mV	3.75 pW	——	Finger	Bending	——	[98]
BNT-BKT nanofiber	Film	0.49 V	6.615 nW	——	Finger	Bending	——	[99]
Polymer								
PVDF	Film	2 V	2 nW	0.32 μW cm^{-3}	Finger	Clicking	$2.8 \times 0.8 \times 0.0028$ cm^3	[100]
Composite								
ZnO nanowire + PVDF	Film	0.33 V	0.02 μW	0.74 μW cm^{-3}	Finger	Folding	$3 \times 3 \times 0.003$ cm^3	[101]
$BaTiO_3$ + P(VDF-TrFE)	Film	8 V	7.2 μW	102.9 μW cm^{-3}	Back of hand	Grabbing and releasing	$2 \times 2 \times 0.0175$ cm^3	[102]

6.2.1 | Ceramics

Since wrist motions are low-frequency and can occur in various acceleration directions, a frequency up-converter with a novel piezoelectric structure was designed and fabricated to harvest energy from wrist motions.[103] The wrist-worn energy harvester consisted of six PZT trapezoidal beams with embedded magnets to form a magnetic plucking configuration. The PZT beams were sputtered with Ni on both sides to increase the thickness of the substrate to 5.4 μm (Figure 5A). The assembled wrist-worn device was located on an aluminum arm to simulate the swinging motion. The equipment generated electrical energy from gentle movements such as slow arm wings and small wrist rotations. The maximum output power was 156.6 μW when jogging.

Since nanogenerators have recently been developed showing potential as power sources for wearable applications, there is one method to enhance the output performance of ZnO nanogenerators via a p−n junction. A wearable-on-skin piezoelectric device based on ultra-thin solution-derived ZnO p−n homojunction films was reported for hybrid functions.[104] The typical method to form a p-n heterojunction involves covering an n-type doped ZnO film with an array of ZnO nanowires with a p-type conducting polymer. In the device, two layers of ZnO with n-type and p-type polymers were used instead, due to improved chemical stability and mechanical durability. The piezoelectric film fabricated by this p-n junction ZnO nanogenerator was used to detect small-scale muscle movements and harvest biomechanical energy. Their device was able to recognize different hand gestures through electrical signals generated from a wrist attachment. The peak output voltage for the condition of all fingers bending was 0.6 V, and the peak current was around 150 pA.

6.2.2 | Polymer

A curved piezoelectric generator was presented in another favorable structure for wearable applications for low-frequency vibrations.[105] The device consisted of two curved piezoelectric generators connected back-to-back. Each generator comprised a curved polyimide (PI) substrate and two PVDF piezoelectric films arranged in a sandwich structure (Figure 5B). The PI substrate acted as a passive layer which effectively subjected the PVDF layer to vertical force, moving the neutral plane towards the inside of the PVDF layer. The PI layer also acted as an active layer to return the piezoelectric material to its original shape, and the curved structure allowed intensification of the applied force on the piezoelectric layer. The PI substrate was configured to enable a uniform stress

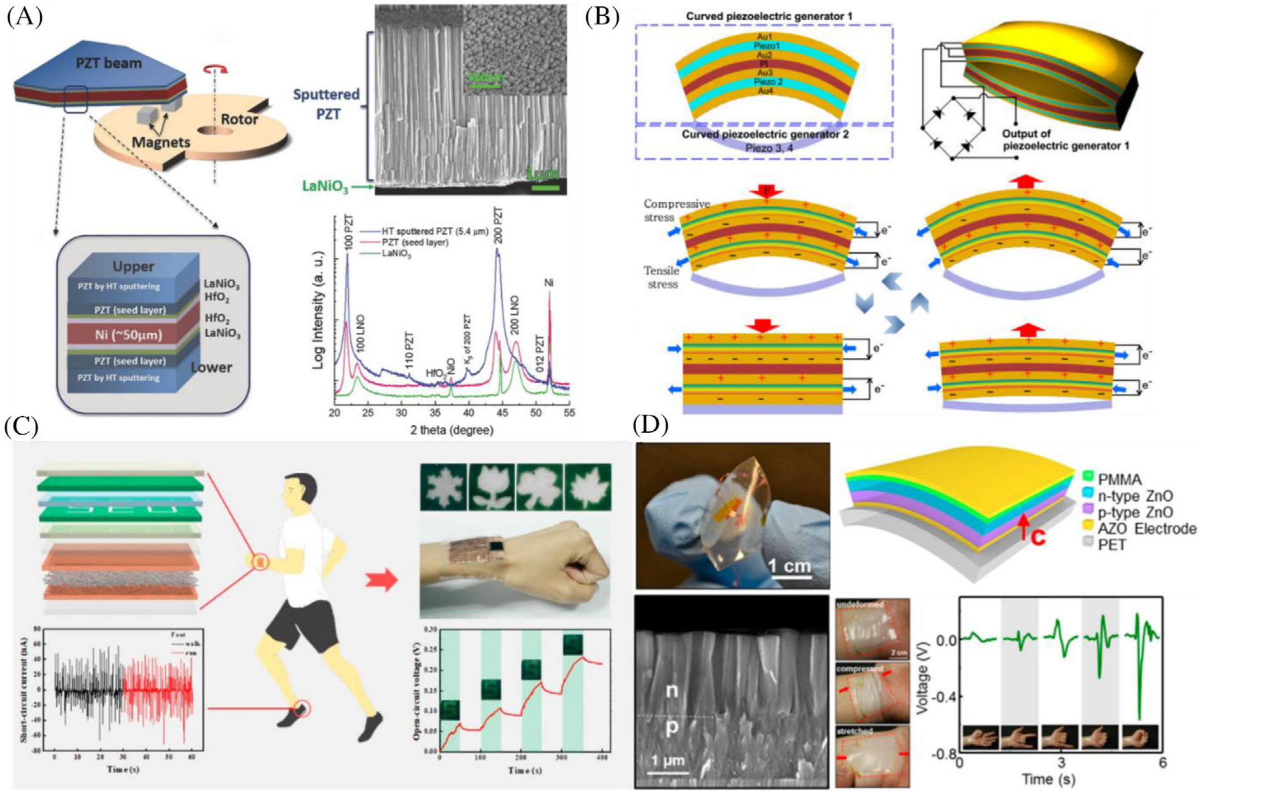

FIGURE 5 A, Schematic diagram of the rotational harvester with bimorph PZT beam as well as the FESEM images. Reproduced with permission from.[103] B, Structure and working mechanism of the curved piezoelectric generator. Reproduced with permission from.[105] C, Working principle of the nanogenerator and patterned supercapacitor for harvesting the energy of human wrist. Reproduced with permission from.[106] D, Photograph and schematic diagram of the homojunction nanogenerator. Reproduced with permission from[104]

profile across the entirety of the PVDF surface. The output voltage of the curved piezoelectric generator, with all PVDF films connected in parallel, was measured to be up to around 155 V, and the instantaneous power density was approximately 3.9 mW cm^{-2} for finger tapping motions. A single layer of the curved piezoelectric generator can be attached on the watch strap to harvest power from various wrist motions. It was recorded that most wrist motions could generate output voltages in excess of 5 V and output currents over 5 μA. The superior performance of the curved piezoelectric generator made it possible to harvest electrical energy from human activity and body movement.

A self-powered system was designed to integrate energy harvesting, conversion, storage, and indication technologies to scavenge energy from human motion.[106] An electrochromic supercapacitor achieved the energy storage function and indication function where the energy scavenged from human activities was converted to electricity using electrospun PVDF nanofibers. The system mounted on the wrist harvested energy from palm impact motions and converted alternating current to direct current using a rectifier for charging the electrochromic supercapacitor. The supercapacitor was able to change its color in the continuous charging or discharging processes, as shown in Figure 5C. It took 180 s for the voltage of the self-powered system to rise from 0 to 0.289 V in the continuous palm impacting condition, in comparison to 220 s for self-discharging to 0.189 V when hand movements were stopped.

6.2.3 | Composite

A single-cantilever structured piezoelectric generator mounted on the wrist was demonstrated by Bai et al. to harvest mechanical energy from the upper limb.[107] When volunteers performed various daily activities (for example cooking, walking, and clapping hands), the watch-sized energy harvester generated an average output power of around 50 μW. Although the size of the cantilever is small, the harvester operates in a bending mode, which requires more space around the tip mass area.

Moreover, bio-compatible piezocomposite films without additional structures were used to monitor biomechanical movements as well as transfer these tiny deformations into

TABLE 4 Comparison between different materials and structures for piezoelectric energy harvesting from wrist

Material	Structure	Output voltage	Output power	Power density	Motion	Size	Ref
Ceramics							
PZT	Frequency up-conversion	2 V	158.8 μW	15.9 mW cm^{-3}	Hand shaking	$12 \times 1.54 \times 0.00054$ cm^3	[103]
ZnO nanowire	Film	0.6 V	90 pW	102.9 pW cm^{-3}	Finger bending	$5 \times 5 \times 0.035$ cm^3	[104]
Polymer							
PVDF	Curved	3-25 V	22.5-3000 μW	19.5-2604.2 μW cm^{-3}	Wrist twisting, wrist bending, elbow pivoting, running, tapping the watch, and grabbing	$1.2 \times 16 \times 0.06$ cm^3	[105]
PVDF nanofiber	Stacked	4.7 V	451.2 nW	——	Palm impacting	Thickness: 4.5 μm	[106]
Composite							
PZNN-PLZT	Cantilever	5 - 40V	1.4 -266.0 μW	9.72 - 1847.2 μW cm^{-3}	Slamming on table, shaking, cooking, running, walking, walking with hand hitting the body, typing on keyboard, hand clapping, jumping, gesticulating	$4.5 \times 0.8 \times$ 0.04 cm^3	[107]
BCTZ/AgNW+ PDMS	Film	10 V	8 μW	——	Wrist bending	3×3 cm^2	[108]

electricity.[108] An energy source with $0.5(Ba_{0.7}Ca_{0.3})TiO_3$–$0.5Ba(Zr_{0.2}Ti_{0.8})O_3$ (BCTZ) and filler silver nanowires (AgNWs) were blended with a PDMS matrix to produce a flexible lead-free piezoelectric nanocomposite. The nanogenerator harvested energy from human articular motions such as wrist bending and produced 8 μW of output power

In summary, comparisons between different types of piezoelectric energy harvesters for the wrist are shown in Table 4. Ceramic materials still deliver highest power densities, and frequency up-conversion is the most effective method of scavenging mechanical energy from low-frequency movements. However, their bulky nature makes them uncomfortable for the wearer. Therefore, piezoelectric polymers are a better choice for energy harvesting from the wrist.

6.3 | Arm

In this section, we discuss energy harvesting from the upper arm, forearm and elbow. During gait, the arms usually swing back and forth periodically. This is accompanied by certain bending, which makes the arms generate high mechanical energy. Moreover, due to the size of the arms, there are less constrictions for size when designing such harvesters.

6.3.1 | Ceramics

Frequency up-conversion devices are widely used in piezoelectric energy harvesting due to the low frequency and random excitation of the human motion. A wearable vertical-vibration frequency-up-conversion device was designed for generating electricity from the human joint.[109] A magnet and a micromachined nickel cantilever were individually fixed on a PDMS film using two glass pedestals, and a PZT film attached on the top surface of the cantilever (Figure 6A). In the initial state, the end of the ferromagnetic cantilever was pulled into contact with the magnet. When the PDMS substrate was extended, the piezoelectric cantilever separated from the magnet and caused free resonance at its resonance frequency. When the substrate rebounded, the magnet attracted the cantilever again. The device can be mounted on the human joints where the ends of the substrate were bonded on both sides of the joints. The joint rotation allowed the release/pull-in cycle to repeat, where the low-frequency horizontal stretching led to high-speed vertical resonance.

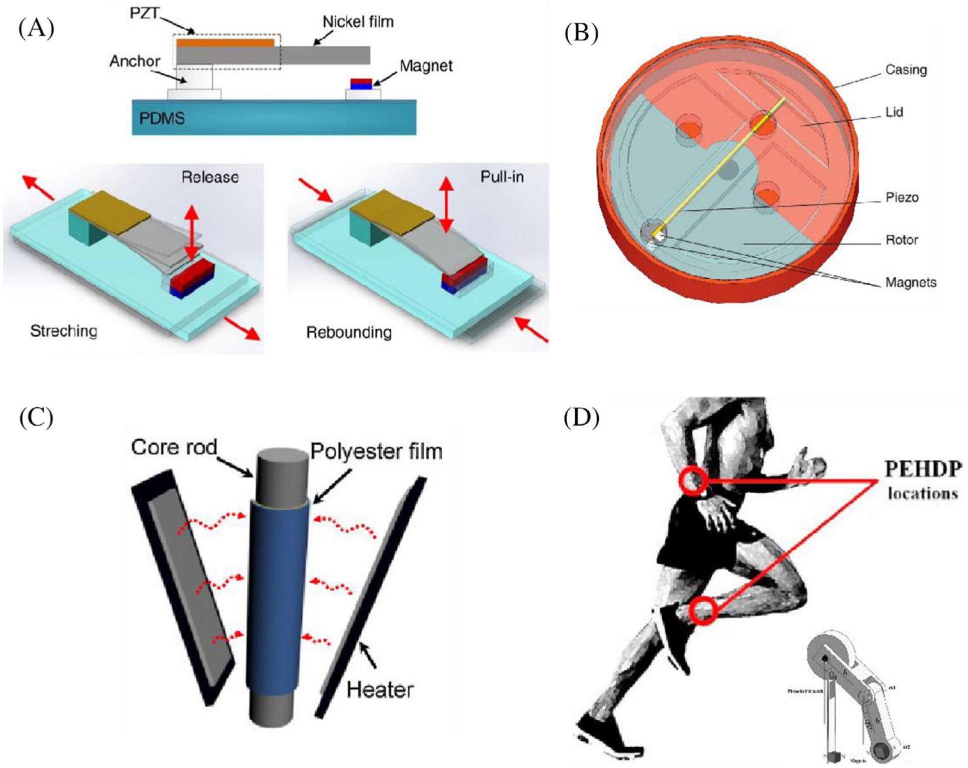

FIGURE 6 A, Structure and working principle of vertical-vibration frequency-up-conversion device. Reproduced with permission from.[109] B, Schematic diagram of a rotational piezoelectric harvester prototype. Reproduced with permission from.[110] C, Schematic of a shell structure of a piezoelectric energy harvester. Reproduced with permission from.[111] D, Structure of the double pendulum system and locations attached on the human body. Reproduced with permission from[113]

Therefore, the ultra-low frequency limb movements can trigger high resonance up to hundreds of Hz based on the frequency-up-conversion structure. Different limb movements were tested when the flexible device was attached on the elbow. A stable peak-to-peak voltage of approximately 7.5 V was achieved, and the maximum output power was 0.457 μW when the user was running fast.

Another type of frequency up-conversion piezoelectric harvester was developed that consisted of an eccentric proof mass in the form of half-disc with a permanent magnet inside (Figure 6B), and a ceramic piezoelectric beam with a second magnet on its tip.[110] Under external excitation, the movement of the semi-disc rotor caused magnetic coupling, which resulted in the initial deflection of the beam tip. After releasing, the vibration of the beam decayed at its natural frequency, allowing energy to be harvested. The system was mounted on the upper arm during running. Initially, the maximum output power reached 7 W, but then experienced a significant decline, principally due to the excessive magnetic coupling leading to over-stressing of the piezoelectric beam. Increasing the gap between the two magnetic masses can address this problem. In fact, when the device was continuously rotated at a frequency of 2 Hz with lower magnetic coupling, the output power reached 43 W, and the power density was 23.2 W cm^{-3}.

6.3.2 | Polymer

Slow and irregular movement is always a challenge for piezoelectric generators to harvest energy from the human body. To overcome this, novel structures are necessary. A novel shell structure for a flexible piezoelectric power harvester was designed by using PVDF film attached to a curved polyester substrate (Figure 6C), which was able to efficiently convert mechanical energy into electrical energy during the fast state transition of the shell structure.[111] When a bending force was applied on the shell structure, it shifted between the initial state and the bending state, and the PVDF layer produced a high output voltage during the fast transition. The output voltage of the shell structure was proportional to the angular velocity. The maximum output voltage was >65 V at a folding angle of 80° with a transition frequency of 3.3 Hz when the shell curvature was larger than 300 m^{-1}, which is larger than the flat structure whose peak output voltage was less than 10 V. The maximum power density was 2.18 mW cm^{-2}

with an optimum 90 kΩ load resistance. However, the durability of the shell structure was relatively low, since the adhesion layer between the PDVF film and electrons was brittle, which resulted in the electrodes to easily peel off. Another challenge for such a shell structure was the reduced curvature after repeated folding and unfolding. In this case, structural modification or shape-memory alloy materials used in the substrate material may be invaluable in overcoming this problem. For harvesting energy from the human body, the shell structures were embedded into the fabrics, which were then fitted on the elbow joint and finger. The peak power density achieved was 4.92 mW cm^{-3}, and this was measured when ten fabrics were worn on the elbow.

6.3.3 | Composite

In addition to frequency up-conversion, nonlinear structures can broaden the operating frequency of kinetic energy harvesters, allowing them to operate effectively in random vibration environments.[112] Moreover, to deal with low-frequency vibrational energy, double pendulum systems interacting with magnetic forces have been demonstrated promising performance in terms of energy harvesting.[113] The setup by Izadgoshasb et al. consisted of a rectangular aluminum beam with a commercial piezoceramic patch, and a magnetic tip mass attached to the end of the aluminum beam (Figure 6D). Two 90 mm arms were attached to the aluminum beams with two strong neodymium magnets. The system was intended for attachment on the human arm to use the swing motion in daily activities. The harvested power from arm motions during walking and jogging were 45.95 and 76.25 μW, respectively. Furthermore, it was reported that the size of the double pendulum system could be easily downsized for wearable devices such as battery-less quartz watches.

A spherical composite bead-based nanogenerator (S-CBNG) was enabled to power wearable devices and acted as a self-powered wearable flexion sensor.[114] A $BaTiO_3$ composite was fabricated through ionotropic gelation with a PDMS matrix. The strip based CBNG had high sensitivity and output performance, which generated a peak output current (227 mA) and voltage (80 V) under relatively low machinal pressure (1.70 kPa), and the output power density was 16.14 Wm^{-2}. Meanwhile, the S-CBNG can be used as a non-invasive wearable sensor to capture tendon force from finger movements when wearing on the forearm. The direct output signal could be used to detect and classify different finger movements. The relative simplicity and practicality of the ionotropic gelation fabrication process has made the sensor competitive in terms of price and large-scale production.

In summary, due to the large area of deformation and the low frequency of movement, most energy harvesters located on the arm focus on structural innovations. In Table 5, we show that the performance of PVDF devices with shell structures are clearly more promising for harvesting energy from the arm in comparison to other devices in terms of wearability and power generation.

6.4 | Shoulder

In comparison to other upper limb areas, fewer devices have been developed for harvesting energy from the shoulder, which may be due to its low flexibility and its low frequency of movement. In this section, we discuss the main methods used for converting energy from this upper limb area.

6.4.1 | Ceramics

During gait, there is a subtle vertical displacement of the shoulders, which means that a backpack can convert mechanical energy from these vertical movements into electricity. Therefore, a novel backpack was proposed to harvest energy during wearer's gait.[115] The strip buckle of the backpack was replaced by a mechanically amplified piezoelectric stack actuator so that the relatively low forces produced by the backpack can be converted into high forces on the piezoelectric stack. In the testing process, a 220 N steel plate was placed into the backpack acting as the load. The results showed that an average power of approximately 0.4 mW could be obtained from this system.

6.4.2 | Polymer

Another energy harvesting backpack was achieved by replacing traditional straps of the backpack with those made from PVDF piezoelectric material (Figure 7A).[116] Compared with a traditional pack, this backpack provided no additional stress or load to the wearer. As the wearer walks with the backpack, the differential forces between the wearer and the backpack would be transferred to the polymer straps, which converted the applied force to electrical energy. Such technology was able to generate 45.6 mW average power using two 52 μm thick piezoelectric straps. In the following decade, developed and optimized shoulder straps enabled better operation in wet conditions.[117] The textile band was fabricated using melt-spun continuous microfibres with a conducting core surrounded by PVDF, as shown in Figure 7B. Water increased the electrical contact surface area between fibres,

TABLE 5 Comparison between different materials and structures for piezoelectric energy harvesting from the arm

Material	Place	Structure	Output voltage	Output power	Power density	Motion	Size	Ref
Ceramics								
PZT	Elbow	Frequency-up-conversion	7.5 V	0.457 μW	——	Elbow rotation	——	[109]
M1100 ceramic (Johnson Matthey)	Upper arm	Frequency-up-conversion	——	43 μW	23.2 μW cm^{-3}	Running	——	[110]
Polymer								
PVDF	Elbow	Shell	33 V	0.21 mW	4.92 mW cm^{-3}	Bending arm	$3 \times 0.6 \times 0.0237$ cm^3	[111]
Composite								
M2814-P2 (Commercial piezocomposite)	Forearm	Double pendulum	——	76.25 μW	——	Walking, jogging	——	[113]
$BaTiO_3$ + PDMS	Forearm	Spherical	60 mV	0.4 nW	0.022 nW cm^{-3}	Finger flexion/extension	$7.5 \times 1.5 \times 1.6$ cm^3	[114]

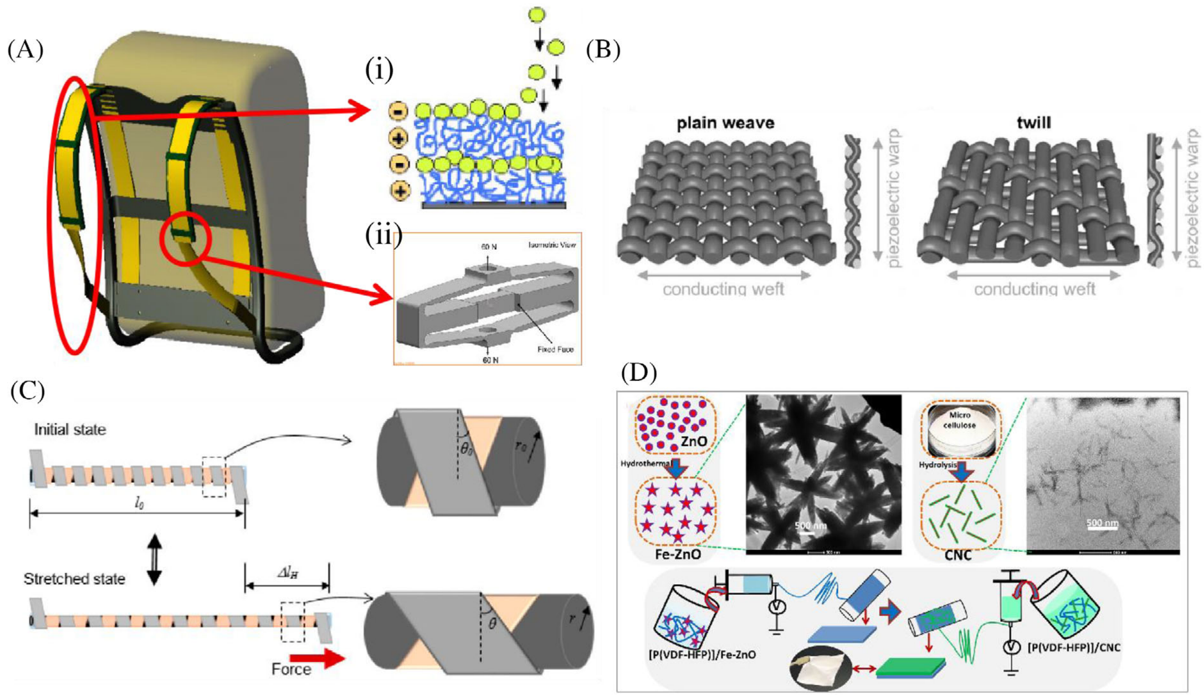

FIGURE 7 A, A backpack with (i) piezoelectric polymer straps. Reproduced with permission from,[116] (ii) piezoelectric strip buckle. Reproduced with permission from.[115] B, Schematics showing produced plain weave and twill textile architectures for the piezoelectric shoulder straps. Reproduced with permission from.[117] C, Schematic diagram of a stretched helical piezoelectric energy harvester. Reproduced with permission from.[118] D, Image showing the procedure for fabricating the fiber mat. Reproduced with permission from[120]

demonstrating that the device performance was enhanced under wet conditions. When the twill-woven textile band was sewn into the shoulder strap of a laptop case, it generated around 1 μW after an initial charging time.

In addition to the backpack, there has been interest in developing smart clothing for piezoelectric energy harvesting. These are perhaps more suitable for wearable applications, since they cover large areas of the human body. For example, a flexible and stretchable helical structure was proposed by Kim et al. and Yun et al., which was knitted into a garment and was able to harvest energy from various stretching movements.[118,119] The PVDF strap and fabric band formed two helical structures in counter directions around an elastic core. When the helical

TABLE 6 Comparison between different materials and structures for piezoelectric energy harvesting from the shoulder

Material	Structure/device	Output voltage	Output power	Power density	Motion	Size	Ref
Ceramic							
——	Stacked actuator	7 V	0.4 mW	——	Walking	——	[115]
Polymer							
PVDF	Shoulder straps	100 V	45.6 mW	14.33 mW cm^{-3}	Walking	$120 \times 5.1 \times 0.0052$ cm^3	[116]
PVDF	Textile	4 V	1 μW	0.47 μW cm^{-3}	Walking	$2.5 \times 20 \times 0.043$ cm^3	[117]
Composite							
PVDF-HFP+ CNC/ZnO	Textile	0.55 V	——	——	Shoulder movement	——	[120]

harvester was stretched, the helical structure experienced torsional stress and longitudinal tensile stress from the extensional motions (Figure 7C). The PVDF was therefore able to consistently generate electrical energy during the continuous stretching and contraction motions. The helical harvesters were embedded into the different joint regions of the commercial garment—shoulder, elbow, hip, and knee—to investigate the output performance of general stretching human motions. During the maximum stretching motion of the shoulder, the change in length was around 2 cm, and the output voltage was 10 V with a 3 mm elastic core diameter and 5 mm PVDF width.

6.4.3 | Composite

More recently, another stretchable piezoelectric nanogenerator was demonstrated in 2019.[120] The nanogenerator was fabricated using two layers of polyvinylidene fluoride hexafluoropropylene (PVDF-HFP) hybrid nanocomposites, which contained the cellulose nanocrystals and the Fe-doped nano ZnO material. The fabrication process is shown in Figure 7D. In order to demonstrate the energy harvesting efficiency, the piezoelectric composite was placed on the finger, elbow and shoulder. During the shoulder movement, it was found that the nanogenerator attached on the cloth can generate 1.1 V peak-to-peak output voltage.

In summary, the performance of different piezoelectric energy harvesters from the shoulder is demonstrated in Table 6. Smart textile seems more convenient for harvesting energy from the shoulder due to their comfortable materials and flexibility.

7 | CONCLUSIONS AND RECOMMENDATIONS

Current progress in the field of piezoelectric energy harvesting enables the development of new devices and materials for harvesting mechanical energy directly from the human body. As we mentioned, the upper limb is an attractive location for harvesting energy from human motion for powering healthcare devices. In this review, we presented a thorough summary of the latest trends, materials, architectures and technologies used in harvesting energy from the hand, wrist, arm, and shoulder movements. We also provided a systematic comparison in the performance of these technologies.

We concluded that ceramic materials have been used to achieve highest power densities for harvesters located on the hand and wrist. In fact, power densities reached 400 μW cm^{-3} for hand harvesters and 15.69 mW cm^{-3} for harvesters located on the wrist. Polymers with good flexibility are more suited to harvesting energy from the arm and shoulder, since they can be tightly attached to the human body and allow a larger range of stretching motions. The power density achieved from piezoelectric transducers attached to the arm and shoulder are 4.92 and 14.33 mW cm^{-3}. In summary, our investigations show that the wrist is the best place for harvesting energy from the upper limb, since it yields the highest power density.

Although considerable achievements have been made in wearable self-powered devices, grand challenges still remain for emerging and practical applications. For example: (1) The structure of devices for frequency and amplitude up-conversion to optimize input excitation from human motions. However, such devices tend to be large in size, and the materials are rigid so that they hinder common human movements. (2) At the same time, new materials developed in the laboratory are far from being ready for potential applications. Although some harvesters have been tested on the human body, their reliability, stability as well as compatibility have not been demonstrated for practical applications. In addition, the mass production of new materials has not yet been achieved, and production costs are still high. (3) For self-powered systems, the harvested energy plays an important role in the continuous and stable operation of the whole system. As previously demonstrated in Table 1, most wearable devices need a few tens of milliwatts to power their various constituent components. However, most piezoelectric energy harvesters can only scavenge power in the nW to μW range from the upper limb. Consequently, this power imbalance means that piezoelectric transducers cannot meet the needs of an autonomously driven wearable device.

Various types of harvester configurations and piezoelectric materials can be developed in the near future. (1) More system-level developments are required, for example towards a fully integrated system with energy harvester, energy storage, signal processing circuitry, sensors and communication unit represents a current trend for the future. Additionally, printable electronic devices are opening up a new approach to make systems highly uniform, highly flexible, and small in scale. (2) High performance, flexible, lead-free piezoelectric materials are vital for future wearable electronics, especially as it is likely that piezoelectric ceramics will tend towards lead-free compositions in the future. Thus, novel piezoelectric materials and manufacturing technologies should be developed to make the piezoelectric transducers reliable and enduring in operation. (3) Furthermore, hybrid energy harvesters will enable a significant widening of the input power range. There are already some piezoelectric hybrid applications operating through triboelectric,[121–125] thermoelectric,[126,127] electromagnetic[128] and solar[129] mechanisms.

Overall, the significant progress in energy-harvesting technology provides opportunities and advantages in self-powered wearable applications, which are applicable to personalized healthcare in the future.

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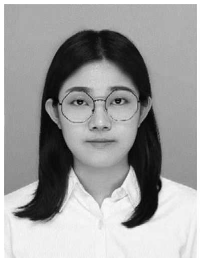

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