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Harvesting Energy from Human Motion for Flexible and Wearable Devices

Literary Review

Materials Engineering/Department of Mechanical and Materials Engineering

Bachelor's thesis

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Flexible and wearable devices have gained interest because of new technological advancements. Harvesting energy from human motion is a clean and reliable option for powering these devices. Piezoelectric, triboelectric and electromagnetic energy harvesters collect energy from mechanical movements and convert it to electricity. Piezoelectric transducers contain materials that can be used to generate electrical charges when mechanical stress is applied to them. Triboelectric transducer's working mechanism is based on electron transfer between surfaces of two materials. Electromagnetic energy harvesters use electromagnetic induction as a power generation method.

This thesis explores different materials and fabrication methods that are used in triboelectric, piezoelectric and electromagnetic energy harvesters and compares different material options to find out the best energy harvester systems for powering flexible and wearable devices. Triboelectric devices can have a high flexibility and good electrical performance primarily in the milliwatt scale based on the obtained results. They can be used for powering self-powered sensors and even electrical watches. Piezoelectric devices can have flexible structures, but the power generation capabilities seem to be lower. Oscillatory electromagnetic energy harvesters perform almost as well as triboelectric harvesters, but the bulky structures of electromagnetic devices means they aren't suitable for flexible devices.

Keywords: triboelectric, piezoelectric, electromagnetic, human motion energy harvesting, flexible wearable devices

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Joustavat ja puettavat laitteet ovat herättäneet kiinnostusta uusien teknologisten kehitysten myötä. Energian kerääminen ihmisliikkeistä on puhdas ja luotettava vaihtoehto näiden laitteiden energiantarpeiden täyttämiseen. Pietsosähköiset, tribosähköiset ja sähkömagneettiset energiankerääjät keräävät energiaa mekaanisista liikkeistä ja muuttavat sen sähköksi. Pietsosähköiset energianmuuntajat sisältävät materiaaleja, joita voidaan käyttää sähkövarausten tuottamiseen, kun niihin kohdistetaan mekaanista rasitusta. Tribosähköisen energianmuuntajan toimintamekanismi perustuu elektronien siirtoon kahden materiaalin pintojen välillä. Sähkömagneettiset energiankerääjät käyttävät voiman tuottamiseen sähkömagneettista induktiota.

Tässä tutkielmassa tutkitaan materiaaleja ja valmistustapoja, joita käytetään tribosähköisissä, pietsosähköisissä ja sähkömagneettisissa energiankerääjissä ja vertaillaan erilaisia niissä käytettäviä materiaalivaihtoehtoja, jotta pystyttäisiin selvittämään, mitkä ovat parhaat energiankerääjät joustavien ja puettavien laitteiden energiantarpeisiin. Tribosähköiset laitteet voivat olla hyvin joustavia ja hyviä sähköisiltä ominaisuuksiltaan. Sähköinen suoriutuminen on kerättyjen tulosten perusteella pääosin milliwattien tasolla. Tribosähköisiä laitteita voidaan käyttää omatehoisten antureiden ja jopa sähköisten rannekellojen energianlähteenä. Pietsosähköisillä laitteilla on joustava rakenne, mutta niiden voimantuottamiskyvyt vaikuttavat olevan alhaisempia. Värähtelevät sähkömagneettiset energiankerääjät suoriutuvat melkein yhtä hyvin kuin tribosähköiset kerääjät, mutta koska sähkömagneettiset laitteet ovat rakenteiltaan kookkaita, ne eivät ole sopivia joustaviin laitteisiin.

Avainsanat: tribosähköinen, pietsosähköinen, sähkömagneettinen, ihmisliike-energian kerääminen, joustavat puettavat laitteet

List of abbreviations:

TENG: Triboelectric nanogenerator

PNG: Piezoelectric nanogenerator

VCSM: Vertical Contact-Separation mode

PZT: Lead Zirconate Titanate

BT: Barium Titanate

PVDF: Polyvinylidene fluoride

P(VDF-TrFE): Polyvinylidene fluoride-trifluoroethylene

BNT: Barium sodium titanate

ZnO: Zinc Oxide

NP: Nanoparticle

PAN: Polyacrylonitrile

AlN: Aluminum nitride

CNT: Carbon nanotube

PDMS: Polydimethylsiloxane

BHmax: Maximum energy product

PA66: Polyamide6-6

HEC: Hydroxyethyl cellulose

GO: Graphene oxide

WPU: Water polyurethane

CMWCNT: Carboxyl multi-walled carbon nanotube

NF: Nanofiber

BTO: BaTiO₃

BITO: Bi₄Ti₃O₁₂

PPy: Polypyrrole

Ag NW: Silver nanowire

PAM: Polyacrylamide

PANI: Polyaniline

PVC: Polyvinyl chloride

HOPG: Highly oriented pyrolytic graphite

LED: Light-emitting diode

Table of contents

1	Introduction	6
2	Background	8
2.1	Piezoelectric Energy Harvesters	8
2.2	Triboelectric Energy Harvesters	10
2.3	Electromagnetic Energy Harvesters	12
3	Materials and methods	15
3.1	Piezoelectric transducers	15
3.1.1	Materials	15
3.1.2	Fabrication	17
3.2	Triboelectric transducers	18
3.2.1	Materials	18
3.2.2	Fabrication	19
3.3	Electromagnetic transducers	19
3.3.1	Materials	20
3.3.2	Fabrication	20
4	Results	21
5	Applications	25
6	Conclusions	27
	References	28

1 Introduction

There is a great number of different movements created by the human body that could be used as an environmentally sustainable energy source and harvesting this energy to power flexible and wearable devices is an intriguing option. Energy harvested from certain human movements such as walking could be used to generate significant amounts of energy if the energy can be harvested effectively. [1] Effective utilization of human body energy should be enough to power wearable electronics. Wearable devices usually require milliwatts to watts of power to operate. [2] Solar and wind power would be environmentally friendly power sources, but they can't produce energy continuously and reliably. Human motion energy harvesting can provide user-dependent energy that is independent of weather conditions. [1]

New technological advancements have sparked interest in developing wearable devices and increasing their flexibility. Flexible wearable devices could include different applications such as human motion monitoring and applications in human-machine interaction field. Many traditional wearable devices are powered by small batteries with a short lifetime and there is a need to replace them often. These batteries come with an environmental cost because replacing them frequently means more raw materials are harvested and disposing of the materials can be a problem. Additionally, battery powered devices are not optimal for flexible devices because of their rigid structures which means that other more suitable methods should be considered. [2–4]

Human motion energy harvesters such as piezoelectric, triboelectric and electromagnetic devices can capture the mechanical energy of human movements and convert the energy into an electrical form. Figure 1 shows the process of using different human energy harvesting and conversion methods to power wearable applications. Efficient conversion of energy can be a challenge and the average power output generated by nanogenerators from low-frequency excitations such as human movements may not be sufficient for independently powering wearable devices. There are several approaches for solving the problem such as improving the piezoelectric performance of piezoelectric harvesters, integrating nanomaterials in the harvester structure and using efficient capacitors to store the energy [4].

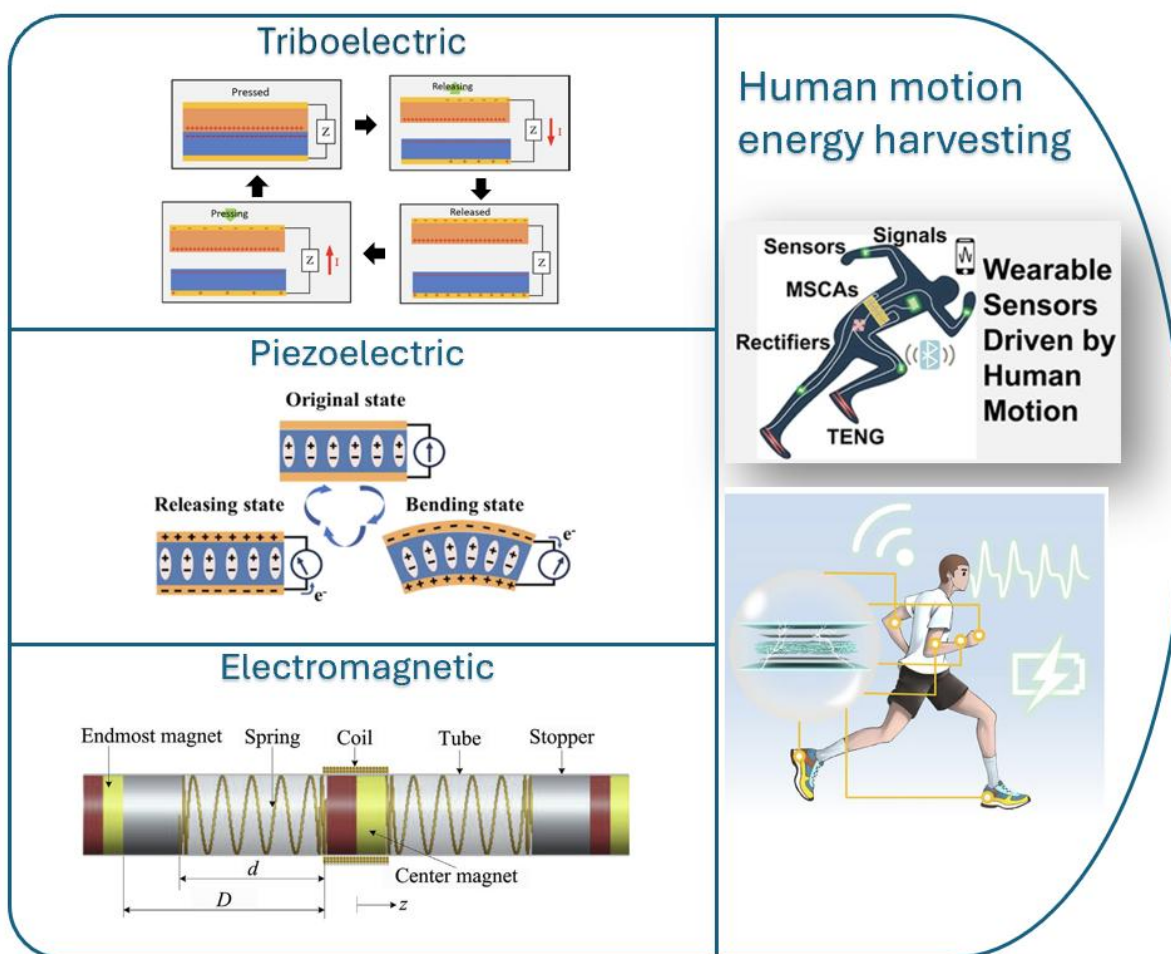


Figure 1. Graphical abstract of human motion energy harvesting. Images reproduced with permissions from [1,4–7]. Copyrights 2025 Elsevier, 2019 Springer Nature, 2024 Springer Nature, 2019 Elsevier and 2025 Elsevier.

This literary review aims to find out which flexible and wearable devices could be powered by harvesting energy from human motion with different methods. It also compares three different types of energy harvesters to figure out which one is the most suitable option for human motion energy harvesting.

Chapter 2 describes the working mechanisms, different types and basic principles of piezoelectric, triboelectric and electromagnetic energy harvesting methods. Chapter 3 describes the materials that are used in the energy harvesters and the fabrication methods. Chapter 4 shows a table of different energy harvesters, and their properties and the obtained results. Chapter 5 discusses the applications.

2 Background

Energy harvesting is a process where energy is collected from different types of sources and converted into usable electrical energy. [3] Energy can be harvested from different ambient sources, including wind, waves, solar radiation, thermal sources and mechanical movements. [8] In human body, in particular, there are different energy sources that could be utilized for energy harvesting, such as mechanical, thermal, and chemical energy sources. Piezoelectric, triboelectric and electromagnetic energy harvesters are mechanical energy harvesters which means that they can convert mechanical energy, such as human body movements into electrical energy. [4]

2.1 Piezoelectric Energy Harvesters

Piezoelectric energy harvester is a device that is made of a material with piezoelectric properties, electrodes and other necessary substitutes. Piezoelectric materials can generate electrical charges when mechanical stress such as bending or pressing force is applied to the material. They have a special crystal structure that lacks a centre of symmetry. The charge distribution of the negative and positive charges in the crystal structure is in balance when external deforming force isn't applied to the structure. When stress is applied to the material, the crystal structure is disoriented and there is an unbalance in the charge distribution and polarization happens. Positive and negative charges accumulate to the opposite surfaces of the structure which creates piezoelectric potential. Piezoelectric potential is used to drive a current through a circuit by attaching electrodes to the material's surfaces. When the external force is removed, the material returns to its original state which induces a reverse current and the potential disappears until the structure is deformed again. [4,9,10] Figure 2 shows the basic working principle of a piezoelectric transducer where current is induced by pressing and releasing the piezoelectric film.

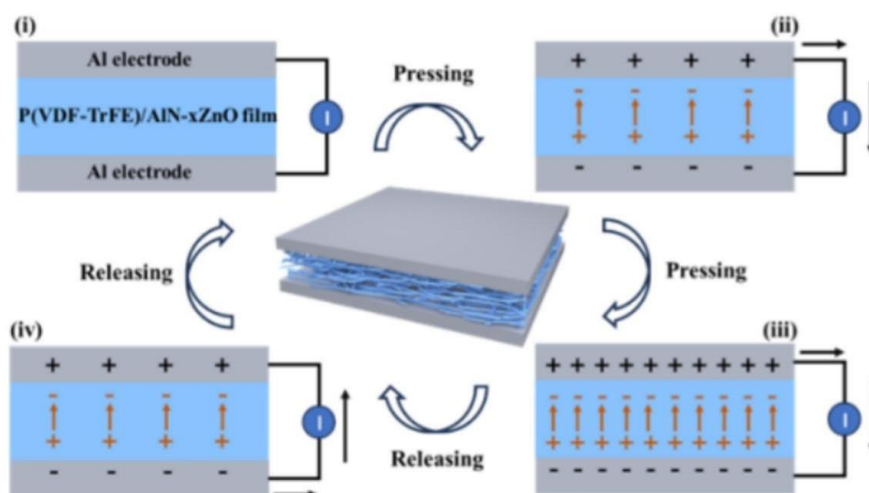


Figure 2. Working mechanism of a piezoelectric transducer. Image reproduced with permission from [11]. Copyright 2025 Elsevier.

Piezoelectric effect is a phenomenon that can be divided into direct and converse piezoelectric effect. The direct piezoelectric effect describes material's ability to be polarized and create an electric field when stress is applied to material. [9,12] The converse effect means that an applied electrical field causes a deformation in the piezoelectric material. [12]

The piezoelectric transducers can be divided into mode 31 (d_{31}) and mode 33 (d_{33}) based on which direction the force is applied to in relation to the direction where the polarization happens inside the material. If the stress is applied in the direction of the polarization, the transducer works in mode 33 and if it is applied perpendicularly in relation to the polarization direction, the transducer works in mode 31. [9] Figure 3 shows the two operational modes. Piezotronic nanogenerators can also be counted as their own operational type. They are nanogenerators that utilize the piezotronic effect for power generation, in which the Schottky barrier is formed between the nanostructure and electrodes. [1]

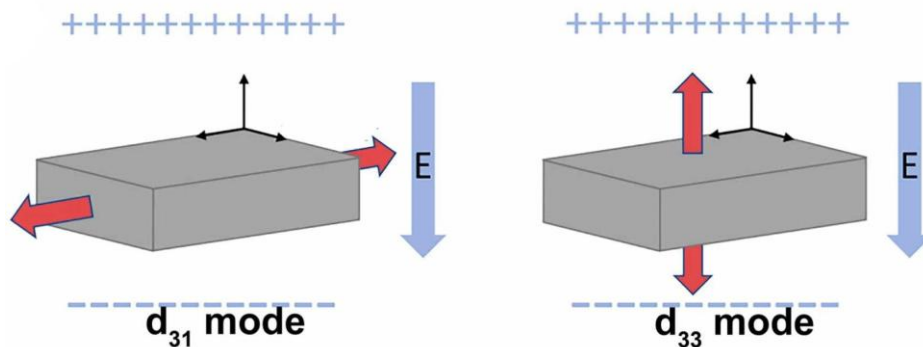


Figure 3: d_{31} and d_{33} operational modes of piezoelectric transducers. Image reproduced with permission from [4]. Copyright 2025 Elsevier.

2.2 Triboelectric Energy Harvesters

Triboelectric energy harvester is made of a positive and negative triboelectric material and electrodes attached to the materials. Triboelectric energy harvester's working principle is based on frictional forces causing imbalances in the surface charges of two materials with different electron affinities. Electron affinity is material's ability to donate or accept electrons when it interacts with other materials. Positive triboelectric materials tend to lose electrons and gain a positive charge, and negative triboelectric materials tend to accept electrons which gives them a negative charge. When two materials with different polarities get in contact with each other, electron transfer happens between the materials which creates opposite and equal charges in the surfaces of the materials. Triboelectrification and electrostatic induction are the main events behind triboelectric nanogenerators (TENGs). Triboelectrification is the part where different materials get in contact and gain opposite surface charges by charge transfer and then are separated from each other. Electrostatic induction happens when charges are redistributed in the presence of an electric field. In TENGs this happens when materials are separated and there is an internal charge imbalance inside the material which results in electron flow through the electrodes. [4,8,13] Figure 4 depicts the working mechanism of a triboelectric transducer working in a Vertical Contact Separation Mode.

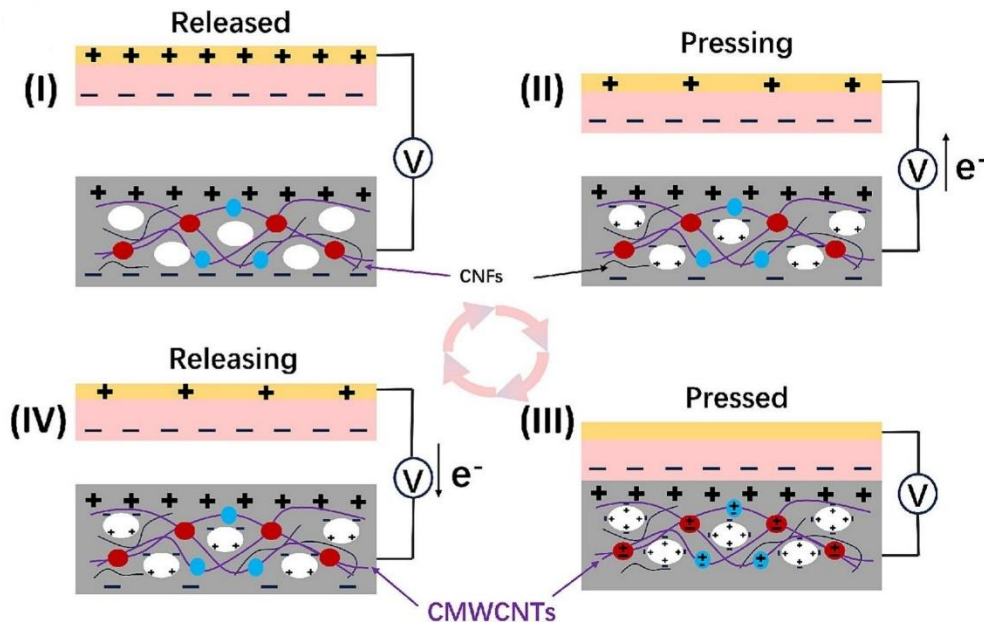


Figure 4: Working mechanism of a triboelectric transducer. Image reproduced with permission from [14]. Copyright 2026 Elsevier.

Triboelectric transducers have four different operating modes. Vertical Contact-Separation Mode (VCSM) is the most commonly used mode where two different materials are pressed together by an external force and then completely separated from each other cyclically. [1] It consists of a positive and a negative triboelectric material and two current collectors that are attached to those materials. The triboelectric layers cause the charge generation whereas the current collector layers allow a smooth flow of current which can be harvested. When the materials come in contact with each other, the surfaces of the materials become positively and negatively charged through electron transfer between the materials. When the parts are separated and have a distance between them, the charges in the surfaces are evened out with an electron flow between the triboelectric materials and the electrodes which generates a current.[8]

In-Plane Sliding Mode is a mode with two triboelectric planes that slide in relation to each other. Contact separation happens when planes are sliding away from each other and the common surface area decreases. When the planes slide back into contact, the charge separation disappears. Single Electrode Mode is a mode where there is a friction layer connected to a grounded electrode layer and a moving part. The moving active layer is moving in and out of contact with the friction layer. The two layers acquire

opposite charges when they are separated which creates a charge in the electrode and there is an electrical current between the ground and the electrode. In the Freestanding Mode, there is a moving part that is sliding freely over two electrodes and the sliding motion creates a current. [1] Figure 5 shows the four operating modes of triboelectric nanogenerators.

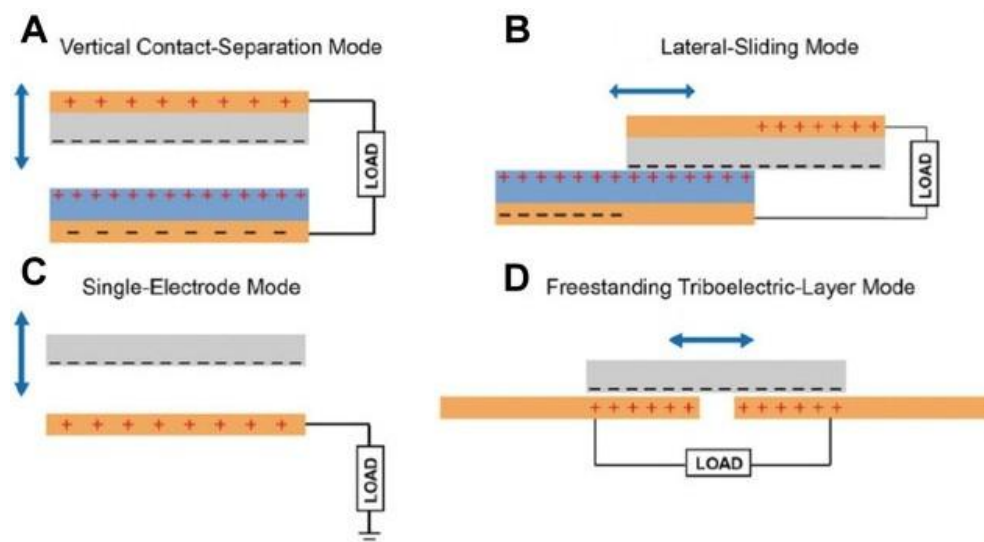


Figure 5: Different types of triboelectric nanogenerators. Reproduced from [15].

2.3 Electromagnetic Energy Harvesters

Electromagnetic energy harvesters are devices that consist of magnets and coils as the primary power generation parts. The working principle is based on electromagnetic induction and Faraday's Law. When a magnet and a coil with a number of turns, are moving in relation to each other, the magnetic field creates a potential difference in the coil. [1] Faraday's Law is depicted in Equation 1

$$\varepsilon = -N \frac{d\Phi_e}{dt}, \quad (1)$$

where ε is the electromotive force that is generated, N is the number of turns in a coil, Φ_e is the magnetic flux density and t is time. [16]

The electromagnetic devices can be divided into three types based on the mechanical movements inside the energy harvesters. The principle of rotary electromagnetic energy harvesters is that human movements rotate a rotary magnet inside an energy harvester, and it generates electricity. The coils stay in one place inside the device. A rotary energy

harvester could be attached to an ankle, and walking or running would rotate the magnet. In oscillatory or vibrational energy harvesters, vibrational movements of the human body are first converted into internal kinetic energy where the magnet moves inside the harvester and then the energy is converted into electrical energy by electromagnetic induction through the movement of the magnet in relation to the coils. The structure is typically tube-like, and the mass can move in limited ways inside the energy harvester. In conventional systems there is a spring and a damper attached to the moving magnet. Oscillatory harvesters can usually utilize lower frequencies than other electromagnetic harvesters. [1,16] Figure 6 depicts an oscillatory electromagnetic energy harvester.

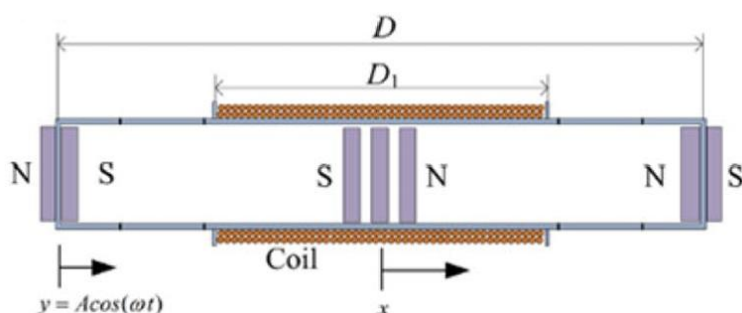


Figure 6: Oscillatory electromagnetic energy harvester. Image reproduced with permission from [1]. Copyright 2019 Springer Nature.

Hybrid electromagnetic energy harvesters harvest energy from linear motion and use an eccentric rotor to channel the energy into a rotational movement of a magnet to increase the power output.[1] Converting mechanical energy into electrical energy with electromagnetic devices is very efficient but they are often big and bulky which may be a disadvantage when designing wearable devices. [12] This is why triboelectric and piezoelectric transducers can be combined with electromagnetic devices to create devices that are smaller than electromagnetic generators but still have a high power output. [1]

Human movements have very low frequencies which means that harvesters have to be able to operate at these frequencies. Harvesting energy from very low frequencies with electromagnetic generators can be challenging, and up-converting methods are one

way to solve this problem, but they are complex in nature. Oscillatory energy harvesters are a simple way to harvest energy from lower frequencies, which is why this thesis focuses on this type of electromagnetic energy harvesters.

3 Materials and methods

Piezoelectric, triboelectric and electromagnetic energy harvesters use different materials and fabrication methods to assemble the devices. The selection criteria for the materials is based on which are the desirable properties in each harvester type.

3.1 Piezoelectric transducers

Piezoelectric materials can be classified in different ways, but the two major groups are piezoelectric ceramics and polymers. Piezoceramics are brittle materials but especially conventional ceramics such as Lead Zirconate Titanate (PZT) have high piezoelectric coefficients.[10] Piezopolymers have lower piezoelectric properties but they are light weight and flexible materials.[1,9] There are several different fabrication methods that can be used to fabricate piezoelectric materials.

3.1.1 Materials

PZT has many advantages that make it an interesting option for piezoelectric applications. It has high Curie temperature and piezoelectric constant of 360 pC/N and it is an affordable option. It is a durable and thermally stable material. PZT can retain its piezoelectric properties in temperatures above 350 °C. However, its brittleness limits its use in flexible applications. In bulk form PZT can't be used for harvesting energy from low-frequency sources because it has high resonance frequency. It also contains lead which makes it toxic and less suitable option for wearable devices. [10,17] However, turning PZT into a nanostructure with electrospinning makes the structure more flexible.[9]

Barium Titanate (BT) is a lead-free option for PZT. It has a perovskite structure and a lower piezoelectric constant (191 pC/N) and Curie temperature (130 °C) than PZT but high dielectric coefficient. BT nanoparticles can be used in composite materials where piezoelectric polymers or ceramics are combined with each other or with other materials. For example, BT nanostructures can be added as fillers into a PVDF matrix or BT nanoparticles can be coated with polyaniline-coated polyvinylidene fluoride-trifluoroethylene P(VDF-TrFE). Combining BT with other materials can improve the

piezoelectric and dielectric properties such as piezoelectric coefficient of the composite materials. [10,17]

Bismuth sodium titanate (BNT) is a lead-free piezoelectric ceramic with high dielectric constant that is stable at room temperature. The dielectric constant could be as high as 114 in a BNT nanoparticle pellet. BNT nanoparticles (NP) can be used together with PVDF film to increase the dielectric constant and the piezoelectric performance.[18]

Zinc Oxide (ZnO) is a semiconducting piezoelectric ceramic with a hexagonal wurtzite structure that is used in different nanostructures such as nanoparticles and nanorods. It is the most commonly used nanomaterial in piezoelectric applications. ZnO nanostructures have a low piezoelectric coefficient but they can be formed in low temperatures and they are biocompatible, flexible and sensitive materials which makes them a good option for flexible and wearable devices. ZnO nanomaterials can be used in composites, for example together with PVDF. [9,10,17]

Polyvinylidene fluoride (PVDF) is a polymeric piezoelectric material. It is biocompatible, chemically stable and flexible and the structure can withstand compression and decompression well which is important for long-term usability of the applications. It has a piezoelectric coefficient of 6-7 pC/N which is high value for a polymer. PVDF has several different crystal phases and some of them are polar. Carbon, hydrogen and fluoride atoms in the polymer structure can be arranged in different conformations that determine whether the structure is polar or non-polar. Polar structures are needed for the piezoelectric performance. The non-polar alpha phase can be converted into a beta phase mechanically at high temperatures and adding nanostructured filler materials can increase the amount of electroactive polar phases. [9,10,17] P(VDF-TrFE) is a PVDF polymer structure with trifluoroethylene as a copolymer. It has larger degree of crystallization than PVDF and has a polar trans conformation and higher operating temperature.[10] polyacrylonitrile (PAN) is a piezoelectric polymer with an inherently polar zigzag conformation which creates a strong dipole moment of 3.5 Debye. It can be used as a filler in PVDF-based composites. [7]

Fillers such as Mxene nanosheets act as nucleating agents and are used to improve the piezoelectric performance in piezoelectric composites. Fillers can improve the

crystallization rate and support an active conformation in PVDF polymers which can be seen as an increase in proportion of β -phases. For example, adding optimized amount of 0.8 wt% of Mxene nanosheets to a PVDF matrix increases the β -phase content from 42.17% to 50.1%. [5] Aluminum Nitride (AlN) is a thermally stable piezoelectric material that can be used as a filler to increase the piezoelectric performance of the harvester. In P(VDF-TrFE) and AlN mix, having 0.1 wt% of AlN increases the β -phase content from 78% to 82% compared to pure P(VDF-TrFE). [11] Carbon nanotubes (CNTs) are conductive nanofillers that effectively create nucleating sites inside a material because of their high surface area. They can accumulate charges and improve the charge transfer by reducing resistance inside the harvester and. Adding CNTs increases the dielectric constant and the β -phase content of PVDF-based composites. However, too high amounts of nucleating fillers can result in agglomeration which disrupts the piezoelectric performance.[7]

3.1.2 Fabrication

Electrospinning is a method in which nanofibers are created from a liquid that contains the desired material. The liquid moves through a small needle called the spinneret and creates a cone structure at the end of the needle when high voltage is applied. The electric field induces charges in the material which creates surface tension in the liquid. Surface tension creates droplets that turn into the cone structure because of electrostatic repulsion. A charged jet comes out of the tip of the cone and it solidifies into nanofibers that are captured by a collector.[10,19]

Spin coating is a method that is used to apply a thin layer of material on top of another material. The coating material is applied on the surface of the other material while the coated material is spinning and the formed centrifugal force ensures that the created layer is uniform. [10,19]

Additive manufacturing or 3D-printing can be used to fabricate three-dimensional structures. There are many methods to 3D print piezoelectric materials such as aerosol jet printing, stereolithography and direct ink writing. The basis of these methods is to build the structure by adding more material one layer at a time. [10,20]

3.2 Triboelectric transducers

Many different materials could potentially be used in triboelectric transducers but the materials with the largest difference in their polarities can transfer electrons more effectively in low frequencies. One of the triboelectric materials should be strongly electronegative and the other one should be strongly electropositive to create a triboelectric energy harvester with a high output. However, other properties of the materials such as biocompatibility and flexibility should be considered when choosing the material and the combination of materials with the highest output isn't always the best choice. [8,21] There are multiple fabrication methods for triboelectric materials. Some of the fabrication methods are the same methods that are used to fabricate piezoelectric materials.

3.2.1 Materials

Aerogels are a group of organic or inorganic porous materials with a very low density and high compressibility. Because of their porous structure and rough surface structure, they have a high specific surface area which increases the effectiveness of the charge transfer in triboelectric transducers. Charge transfer can also occur at the surfaces of the pores which adds to the effect. [21]

Hydrogels are natural or synthetic porous structures that consist of polymeric matrixes and are well suited for flexible and wearable devices. Especially natural hydrogels are very biocompatible and could even be used in wound healing applications. Hydrogels contain a lot of water and they are flexible and have the ability to conform to different surface structures. [13]

PDMS and Ecoflex are silicon based elastomeric polymers with good flexibility, stretchability and biocompatibility which are important qualities when the applications are flexible and wearable devices.[22] Because of the fluorine groups that it contains, PTFE is highly electronegative and it is commonly used in TENGs as a negative triboelectric material. It has other advantages such as friction resistance and its hydrophobic nature.[4,23]

Textile-based TENGs are made of materials such as yarns, fibers and fabrics. Fiber-based TENGs are made of triboelectric materials and conductive materials that are combined into a fiber structure. Core-shell nanofiber yarns have a conductive electrode material in the core and a triboelectric friction layer on the surface of the yarn. The yarn can be woven into a fabric. Another way is to make fabric directly out of triboelectric materials without creating complex yarn-structures.[23,24]

3.2.2 Fabrication

Piezoelectric and triboelectric materials have several common fabrication techniques that can be used with both materials. 3D-printing and electrospinning can be used to fabricate triboelectric materials as well. [21] Textile-based triboelectric materials can be fabricated in part like regular commercial textiles. They consist of different fibers and yarns that are turned into 2D or 3D textiles by weaving or other methods to increase their outputs. 2D fabrics can also be stacked to create a 3D structure.[24]

The sol-gel method is used to fabricate triboelectric and piezoelectric materials. One example of using the method to fabricate triboelectric materials is fabrication of aerogels. The traditional sol-gel method begins with the hydrolysis of a precursor, which is followed by a condensation step which forms sols. Sols can be nanoparticles or other small intermediate structures. The sols form the final gel structure. Another way is building the gel-structure from nanostructures. In this method nanostructures form bigger structures inside a solution by cross-linking. After the gel is formed it can be dried with an appropriate method that preserves the wanted structure.[19,21,25]

3.3 Electromagnetic transducers

In vibrational electromagnetic energy harvesters, there can be different magnet and coil configurations. The magnets are attracted to or repulsed by other magnets in the structures. Different magnet materials have different energy production capabilities and other properties. Choosing the suitable magnet material is important in determining the effectiveness of the harvester. The conductive coils can be made of a simple wire or by using more advanced methods such as additive manufacturing. [26–28]

3.3.1 Materials

The coil has to be made of a conductive material. They are usually made of different metals or alloys such as copper, aluminum or gold. Copper is commonly used in electromagnetic devices because of its favorable properties such as high conductivity and low cost.[29]

The properties of the magnet affect the performance and usability of the electromagnetic transducers. This is why it matters what material is used in the permanent magnets. NdFeb is a commonly used magnet in energy harvesting and it produces energy effectively but has limitations with higher operating temperatures. AlNiCo and SmCo₅ are also common magnets, but they don't produce energy as efficiently.[28,29] Maximum energy product value is one of the most important parameters that defines magnet's performance and it describes maximum stored energy density in a magnetic field. NdFeB magnets have higher maximum energy product (BH_{max}) values (200-440 kJ/m³) compared to SmCo₅ (120-200 kJ/m³) and AlNiCo (10-88 kJ/m³). The Curie temperature of NdFeB is only 310-400 °C compared to SmCo₅ with a value of 700 °C and AlNiCo with a value of 700-860 °C. [28,29]

3.3.2 Fabrication

Simple coils are made of a metal wire that is wrapped around a magnet. These coils are cheap to make but do not have a uniform structure. More advanced fabrication methods are using additive manufacturing methods to create the coil structure. 3D-printing and other methods can be used to fabricate uniform planar coils with smaller diameters. These manufacturing techniques can be used to create small-sized coils with detailed structures.[16]

4 Results

Energy harvesters composed of different materials have different electrical properties and other properties related to their suitability in flexible and wearable devices. Some of the characteristics of the devices are compiled in Table 1. This comparison table presents examples of different piezoelectric, triboelectric and electromagnetic energy harvesters that are composed of different materials and compares performances and properties of each device.

Serial	Harvester type	Materials used	Maximum Voltage	Maximum short circuit current	Maximum power density	Maximum power	Durability/voltage output stability	Biodegradable	Flexible	Piezoelectric coefficients	Ref
1	Piezoelectric	PZT/P(VDF-TrFE)	4 V (bending), 8 V (pressing)	180 nA	Not found	Not found	Steady output after 2000 cycles	Not found	Yes	d_{33} , 200 pm/V (PZT films)	[30]
2	Piezoelectric	MXene/PVDF	20 V (walking), 30 V (running), 3.1 V (arm bending), 120 V (Jumping)	134 nA	Not found	43.59 nW	Relatively steady output over 5000 cycles	Not found	Not found	Not found	[5]
3	Piezoelectric	P(VDF-TrFE)/AlN/ZnO	23 V	65 nA	Not found	Not found	Not found	Not found	Yes	d_{33} , -69 pC/N	[11]
4	Piezoelectric	BNT/PVDF	19 V	1.2 μ A	3.5 mW/m ²	Not found	Stable output over 5000 cycles	Yes	Yes	41-45 pC/N	[18]
5	Piezoelectric	PVDF/PAN/CNT	13.7 V	0.90 μ A	0.75 μ W/cm ²	Not found	Output relatively stable after 10 000 cycles	Not found	Yes	d_{33} , 19 pC/N	[7]
	Harvester type	Materials used	Maximum Voltage	Maximum short circuit current	Maximum power density	Maximum power	Durability/voltage output stability	Biodegradable	Stretchable	Breathable	Ref
6	Triboelectric	PTFE nano-fibers	206 V	16.3 μ A	1.04 W/m ²	1.6 W	Output over	Not found	Not found	yes	[23]

		doped with graphene/PA66 nanofiber					10,000 cycles				
7	Tribo-electric	Carbon-based aerogel (HEC/GO/WPU/CMWCNTs/Carbon NFs)/BTO and BTO NPs/PTFE	372.35 V	18.72 μ A	1,875 W/m ²	3.01 mW	3600 cycles with relatively stable output	Not found	Not found	Not found	[14]
8	Tribo-electric	PPy/Ag NW/cotton/ammonia blend /PTFE	0.3 V (hand friction/tapping)	Not found	Not found	Not found	4000 cycles with stable output	Yes	Yes	Yes	[31]
9	Tribo-electric	Cellulose hydrogel (cellulose NF/PAM/PANI)/Ecoflex (Silicone Rubber)	150 V	Not found	69 mW/m ²	Not found	6000 cycles with stable output	Yes	Yes	Not found	[32]
10	Tribo-electric	Fluorinated PDMS blend (PTFPMS-PDMS and PDMS)/AgNW (electrode)	1.2 kV	Not found	9.8 W/m ²	0.98 mW	Not found	Not found	Yes	Not found	[33]
11	Tribo-electric	PVC/MXene (Ti ₃ C ₂ T _x)/aluminum	51 V	12.5 μ A	4.94 mW/cm ²	4.94 mW	Not found	Not found	Not found	Not found	[34]
	Harvester type	Materials used	Maximum Voltage	Maximum short circuit current	Maximum power density	Maximum power	Durability/voltage output stability	Number of turns in coil(s)	Mechanism		Ref
12	Electro-magnetic	Copper coil, 4 cylindrical magnets, 1 rectangular	3.56 V, (1,45 V, human walking)	Not found	Not found	Not found	Not found	1200	Three unmoving magnets and one coil, cylindrical magnet rolling in a magnetic plane		[35]

		magnet (materials of magnets unknown)								
13	Electro-magnetic	Nd-Fe-B magnets, copper springs, materials of coils unknown	0.24 V	Not found	Not found	1.15 mW, (0.5 mW walking, 0.7 mW (running))	Not found	Not found	Two cylindrical magnets at both ends of a tube and one moving magnet attached to springs between them, stoppers between the magnets, coil around the tube	[36]
14	Electro-magnetic	Copper coils, highly oriented pyrolytic graphite (HOPG), materials of magnets not mentioned	370 mV, (147,2 mV hand shaking)	Not found	Not found	26.7 μ W	Not found	Not found	One moving (floating) magnet between four coils, two HOPG layers generating repulsive forces and one fixed magnet	[27]
15	Electro-magnetic	Nd-Fe-B magnets, material of coils unknown	0.9 V (hand shaking)	Not found	Not found	2.58 mW, (1.22 mW running)	Not found	200	Two magnets at the ends of a tube, two magnets in the middle, one moving magnet between them, two sets of coils	[26]

Table 1: Comparison table of electric performances and other properties of piezoelectric, triboelectric and electromagnetic energy harvesters.

Human movements such as walking and running have a frequency below 5 Hz. The harvesters have to be able to operate under these conditions.[8] The pressure that human body movements can assert towards triboelectric and piezoelectric harvesters varies in real life applications. In carbon aerogel-based triboelectric generator, the tested pressure range was set in 10 N to 25 N which simulates a physical pressure range from moderate finger pressure movements to a palm strike. [14]

Power range of piezoelectric energy harvester is on a nanowatt scale according to information in table 1 but the value was found only for one piezoelectric harvester which makes it impossible to make real conclusions. Power density is in range of 3.5 mW/m²

to 7.5 mW/m^2 . Maximum voltage is mostly in the range of 8 to 23 V apart from jumping motion in the MXene/PVDF harvester that was measured to produce a voltage of 120 V. Most piezoelectric harvesters have a stable output voltage over several thousand cycles which makes them durable and promising to be used for longer periods of time.

Power range of triboelectric harvesters is 0.98 mW to 1.6 W. Mostly power generation is in the milliwatt scale. Power density range is 69 mW/m^2 to $49,4 \text{ W/m}^2$. Voltage outputs are in the range of 0.3 V to 1.2 kV which is a wide range. Most of the harvesters exhibit a high voltage of several hundred volts. Triboelectric energy harvesters exhibit good durability like piezoelectric harvesters. The electromagnetic harvesters had a power generation range of $26.7 \text{ }\mu\text{W}$ to 2.58 mW. Maximum voltage was in the range of 0.24 V to 3.56 V. Triboelectric harvesters have higher power densities than piezoelectric harvesters. Some of the triboelectric and electromagnetic harvesters have similar power generation capabilities, but triboelectric harvesters have higher power production on average.

5 Applications

When energy harvesters are combined with storage devices, there is a possibility to create self-sustainable devices. Supercapacitors are one way to store the harvested energy and manage the voltage fluctuations effectively and ensure stable performance of the wearable applications. [4] Especially piezoelectric nanogenerators (PNG) have such small power outputs that efficient energy storage systems are important. Another way to make energy transfer more efficient is to have a filter circuit between the PNG and the storage device. The electrical signal is rectified and filtered before storing it in a capacitor. [18] Figure 7 depicts a wearable TENG connected to a supercapacitor.

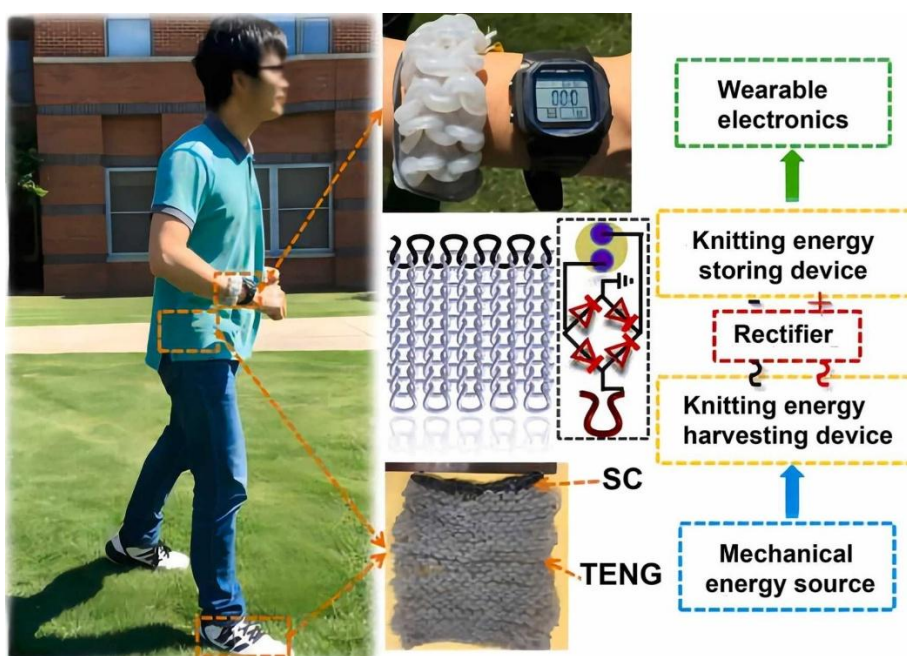


Figure 7: Wearable TENG and a supercapacitor system. Image reproduced with permission from [4]. Copyright 2025 Elsevier.

Triboelectric materials can be used for powering small devices. The most common applications are different sensors. Textile-based triboelectric harvesters can be used as flexible human motion monitors. Sensors can be self-powered and there is a possibility to use multi-dimensional human motion monitoring. PTFE core-shell nanofiber yarn based TENG could power electronic watches. [14,23,31,32]

Piezoelectric nanogenerators can be used in very low-powered devices. One possible application is a medical monitoring system, where bending of fingers sends out a signal.

[11] Piezoelectric nanogenerator made of BNT and PVDF can be used in a safety walker bracelet that emits light when a person is walking and makes the user more visible in the dark. PNG is located under the feet and when it is pressed, it sends signals to an Arduino MC which lights up LEDs when signal is present. [18] The safety walker system is depicted in Figure 8. In addition, PNGs could be used as pressure sensors in wearable devices because the output voltage amplitude depends on the applied pressure. There are possibilities in computer authentication systems based on monitoring typing speed and pressure.[30]

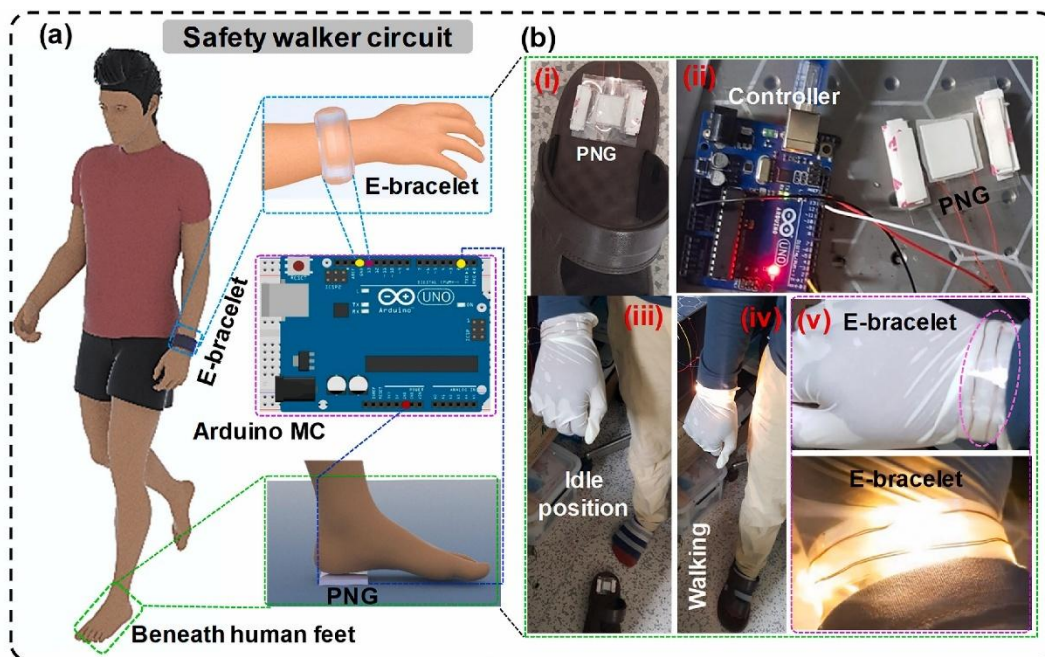


Figure 8: (a) Different parts of the safety walker system. (b) (i) PNG placed inside a shoe (ii) a controller system connected to PNG. (iii)(iv) and (v) E-bracelet that lights up. Image reproduced with permission from [18]. Copyright 2024 Elsevier.

Electromagnetic energy harvesters could be used in low-power devices such as wireless sensor networks and temperature monitors. Powering these devices that work on power level of 0.1 mW shows potential. [6,26]

6 Conclusions

Human motion energy harvesting is a promising field because of the sustainability and reliability of the energy source. However low frequencies of human motion and generally low outputs impose challenges in efficient energy harvesting and ability to power applications. Some electromagnetic energy harvesters operate at higher frequencies and need up-conversion methods. Adding different nanofillers into the piezoelectric structure increased the power output of the devices. Adding fillers such as MXene or nanostructured piezoceramics into a PVDF matrix increased the amount of β -phases present in the material and adding CNTs increased the charge accumulation and charge transfer as well.

Different materials that are used in piezoelectric, triboelectric and electromagnetic energy harvesters were discussed. Many triboelectric materials were flexible and could be used in triboelectric energy harvesters to effectively produce energy and power small devices such as different sensors and even electric watches. Flexibility and effective power outputs of triboelectric devices make them good options for flexible and wearable devices. Many piezoelectric composites that contained PVDF had flexible structures but smaller voltage outputs and power densities than triboelectric transducers. These piezoelectric devices are mostly suited for powering different sensors. Effective electromagnetic human motion energy harvesters use materials such as copper and other metals as coil materials and NbFeB as a permanent magnet. The oscillatory electromagnetic energy harvesters in Table 1 had lower power outputs than triboelectric transducers. Electromagnetic energy harvesters could be used in applications such as wireless sensor networks and other devices that work on power level 0.1 mW. However, electromagnetic harvesters are often bulky structures which makes them unsuitable for flexible devices.

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