Vibration-Energy-Harvesting System: Transduction Mechanisms, Frequency Tuning Techniques, and Biomechanical Applications

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Vibration-based energy-harvesting technology, as an alternative power source, represents one of the most promising solutions to the problem of battery capacity limitations in wearable and implantable electronics, in particular implantable biomedical devices. Four primary energy transduction mechanisms are reviewed, namely piezoelectric, electromagnetic, electrostatic, and triboelectric mechanisms for vibration-based energy harvesters. Through generic modeling and analyses, it is shown that various approaches can be used to tune the operation bandwidth to collect appreciable power. Recent progress in biomechanical energy harvesters is also shown by utilizing various types of motion from bodies and organs of humans and animals. To conclude, perspectives on next-generation energy-harvesting systems are given, whereby the ultimate intelligent, autonomous, and tunable energy harvesters will provide a new energy platform for electronics and wearable and implantable medical devices.

1. Introduction

Energy consumption is a major limiting factor for developing the next generation of wearable electronics, sensors and actuators, and implantable devices. There is a tremendous interest to make these devices self-containable with their own renewable power supply to maximize the use and performance of these devices. Moreover, recent advances in micro-electronics technology have reduced the power requirements of these electronics and wearable/implantable devices to the level of milliwatts [1−4] thus it is becoming increasingly feasible to implement self-power by nonconventional power sources. One promising solution is to use energy harvesters, which convert ambient energy to electrical energy. ID Techex [5] summarized the current energy harvesting (EH) market and discussed about the potential applications in areas such as healthcare, electronics, and automotive applications, with emerging uses such as a potential power source for biomechanical devices also envisioned [6−8].

There are a variety of ambient source candidates for EH, such as thermal, solar and wind energy, mechanical energy from ocean waves, as well as mechanical vibrations and human motions. Among them, vibration-driven energy harvesters offer the most promising solutions, since vibrations provide great potentials as a high power density and long lifetime energy source [9,10] and the body of living subjects has a variety of available energies [11,12]. For vibration-based energy harvesters, four primary energy harvesting mechanisms are used, i.e., piezoelectric [13−21], electromagnetic [22,23], electrostatic [24,25], and triboelectric transductions [26−31]. Although these mechanisms have been widely investigated as a means to generate electrical energy, one of the grand challenges for vibration-based energy harvesting (VEH) is to tune the resonant frequencies to enable the device to optimally harvest energy in various environments [32,33].

In general, possible solutions are resonance-based frequency tuning and expanding the effective bandwidth of the energy harvesting system. Therefore, this review specifically addresses both methods for vibration-based energy harvesting. On the other hand, human motions (some of them are also based on VEH mechanisms) provides a particularly compelling energy source to power the wearable and implantable devices [11,12,34,35] for instance, arm and leg movements, breathing, heart’s systole and diastole dynamics, among many other examples.

There have been a number of published reviews on the topic of generic energy harvesting, and yet most of recent work is primarily focused on the materials [8,36,37] harvesting approaches [38−41] micro-electromechanical systems or nanotechnology enabled devices [42−46] and storing circuits [47−49]. By contrast, the scope of this review is confined to the vibration-based energy harvesters (as illustrated in Figure 1a,b). We start by providing an overview of four vibration-based energy harvesting mechanisms, including piezoelectric, electromagnetic, electrostatic, and triboelectric energy harvesting. It is to be noted that frequency is most essential property of the vibration. For vibration-based energy harvesting, the key challenge is how to implement frequency matching between the energy harvester and ambient vibrations with a wider frequency bandwidth for applications where there is a time-dependent, varying source frequency. Therefore, we next discuss the two major approaches (resonance-based tuning and expanding bandwidth).
that can be used to provide a wide bandwidth of environmental source frequencies over which appreciable power can be harvested from vibration based energy harvesters. Furthermore, biomechanical energy harvesting applications, specifically from ultralow frequency in vivo sources and animal/human biomechanical motions, to bioinspired designs for improving energy harvesting outputs, are reviewed in order to reflect on recent progress. Lastly, we conclude by giving our perspectives on the opportunities for future research on energy harvesting systems. By leveraging on the development of smart materials and structures, future research will ultimately lead to optimal energy harvesting performance to implement an intelligent, autonomous, and tunable energy harvester for a variety of applications.

2. Comparison of Mechanisms of VEH

2.1. Generic VEH Model

In general, a vibration-based energy harvesting device can be modeled as a spring–mass–damper system\(^{[50]}\) based on the linear system theory as shown in Figure 2a, which consists of a spring of stiffness \(k_{\text{struc}}\), a mass of \(m_{\text{struc}}\), and dampers denoted as mechanical dashpot \(b_m\) and electrical dashpot \(b_e\), respectively. Here the mechanical dashpot accounts for the energy losses due to structural and viscous damping, while the electrical damping corresponds to the energy harvested through the energy conversion mechanism. Therefore, in this generic model of VEH, the conversion of energy from the oscillating mass to electricity can be considered as a linear damper to the mass spring system. The generator is an inertial device, and when it is vibrating, there is a net relative motion between the mass and the housing (Figure 2a). This relative displacement is able to drive a transducer, which is depicted as a dashpot, such that the conversion of energy (from mechanical to electrical) damps the mass. While this generic VEH model is simple and neglects the complexity of transduction implementation, functional relationships between the model and real VEH device are nevertheless still valid with/without modifications for various types of transducers.

Given a sinusoidal excitation vibration \(y(t) = Y \sin \omega_t t\) (where \(Y\) and \(\omega_t\) are the source’s vibration amplitude and frequency, respectively) the net electrical power generated can be written\(^{[50]}\) as

\[
P = \frac{m_{\text{struc}} Y^2 \left( \frac{\omega_t}{\omega_{\text{struc}}} \right)^2 \omega_t^3}{1 + \left( \frac{\omega_t}{\omega_{\text{struc}}} \right)^2 + 2 \zeta_s \frac{\omega_t}{\omega_{\text{struc}}}}
\]

where \(\zeta_s\) is the total damping ratio which is the sum of mechanical damping ratio \(\zeta_m\) and electrical damping ratio \(\zeta_e\) such that \(\zeta_s = \zeta_m + \zeta_e\), and \(\omega_{\text{struc}}\) is the undamped natural frequency of the vibrating structure, which can be written as \(\omega_{\text{struc}} = \sqrt{\frac{k_{\text{struc}}}{m_{\text{struc}}}}\). When the energy harvesting device is in resonance such that \(\omega_t = \omega_{\text{struc}}\), the power output at resonance \(P_{\text{res}}\) can be simplified as

\[
P_{\text{res}} = \frac{m_{\text{struc}} Y^2 \omega_t^3}{4 \zeta_e}
\]

According to Equation (2), when the device is vibrating in resonance, the power output is dependent on the mass of structure, the amplitude and frequency of the source vibration, and the damping characteristics of the system. As the vibration amplitude and frequency are a function of the environmental vibration source and thus not design variables, the vibrating structure and damping parameters can be optimized to maximize the power output of the energy harvesting device.\(^{[51,52]}\) Figure 2b gives the power output of the energy harvesting device with respect to the ratio of the structure frequency to the source frequency at various damping values for the case where the electrical damping \(\zeta_e\) matches the mechanical damping \(\zeta_m\) of the system (\(\zeta_e = \zeta_m\)). It is clear that the maximum power output can...
be achieved when the structure frequency matches the source frequency \( (\omega_{\text{struc}} = \omega_s) \). Given that the ambient vibration is always random and varies with different frequencies and accelerations, it is challenging to maximize the power output of the energy harvester with a wider frequency bandwidth for applications. Therefore, frequency tuning and broadband technologies for recent research on VEH will be discussed in Section 3.

Typically, there are four transduction methods used in vibration-based energy harvesting: the piezoelectric, electromagnetic, electrostatic, and triboelectric methods. They are all widely used for converting mechanical vibrations to electricity. A schematic of the four harvesting mechanisms are shown in Figure 3.

2.2. Piezoelectric EH

Piezoelectric materials are a subset of a group of materials known as ferroelectrics, which contain an electric dipole due to its molecular structure creating a local charge separation when the material is strained. The piezoelectric VEH approach utilizes the piezoelectric properties of a certain class of multifunctional materials, which results in an electrical charge being produced when the material is mechanically deformed.\(^{[53]}\) Conversely, there also exists the reverse piezoelectric effect, which is the internal generation of mechanical stresses resulting from an applied electrical field. The former effect is useful for sensing applications of piezoelectric materials, while the latter effect can be utilized for actuation. The piezoelectric constitutive equations are presented in Equations (3) and (4)

\[
\delta = \frac{\sigma}{Y} + dE \tag{3}
\]

\[
D = \varepsilon E + d\sigma \tag{4}
\]

where \( \delta \) is the mechanical strain, \( \sigma \) is the mechanical stress, \( Y \) is Young’s Modulus, \( d \) is the piezoelectric strain coefficient, \( E \) is the electric field, and \( D \) is the electrical displacement (charge density), respectively. From Equations (3) and (4) it is clear that the piezoelectric coupling term connects the two equations, which illustrates the energy conversion transduction.
mechanism of piezoelectric materials subjected to external forces or vibrations.

In literature, the most commonly studied design for VEH is the cantilever geometry\textsuperscript{[13]}. This is because with a given applied force, the cantilever beam design has been shown to produce the highest average strain\textsuperscript{[13]}. When developing vibration-based energy harvesters that utilize piezoelectric materials, the resonance frequency of the device is always the frequency at which the highest electrical output is achievable (Figure 2b). As discussed earlier, this frequency depends on the device's configuration, size, and loading conditions. For many ambient vibration sources, vibration frequencies tend to be less than 200 Hz. Recent research has focused on reducing the resonance frequencies of these energy harvesting devices, in order to better operate in ambient vibration environments. For example, in earlier years Glynne-Jones et al. developed a trapezoidal lead zirconate titanate (PZT) cantilever with a steel substrate, that was able to achieve 3 $\mu$W of power while operating at a frequency of 80 Hz\textsuperscript{[54]}. Roundy et al. developed a PZT bimorph cantilever that had a total size of 1 cm\textsuperscript{3} and operated at approximately 80 $\mu$W with a frequency of 100 Hz\textsuperscript{[9]}. Later they designed a multi-degree-of-freedom system that utilized multiple springs and masses. This device was able to produce a broader range of frequency for optimal operation\textsuperscript{[51]}.

However, one of the primary issues with cantilever-based designs is that they typically only work well when operated in a single direction. Much of recent work has focused on designs that can make use of vibrations at a larger range of frequencies from multiple directions or sources. One approach to tap into multiple directions of operation is to utilize the motion of other systems,
such as a pendulum, which moves in a 3D space. For example, Xu and Tang developed a cantilever-pendulum, which has a natural frequency half that of the PZT cantilever beam,[55] but this design was able to produce similar outputs of that of a simple cantilever–mass system. Song et al. designed an energy harvester for the flow of water by utilizing a PZT piezoelectric cantilever attached to a cylinder to create a vortex-induced EH system.[56] Additionally, Li et al. proposed a biresonant structure by coupling together two separate polyvinylidene fluoride (PVDF) cantilevers with different resonance frequencies[57] as shown in Figure 4a. The coupled cantilevers harvested more energy than two individual cantilevers due to the interactions from their collisions at different resonance frequencies. More recently, Bai et al. developed a cantilever-based piezoelectric device that was mounted on both the wrist and head to harvest energy from everyday movements.[58] They were able to harvest a root mean square power of 50 and 20 $\mu$W for the wrist and head respectively.

In addition, designs other than the cantilever beam using piezoelectric method have been studied in detail, each with its own benefits. In earlier years, Umeda et al. proposed a circular diaphragm structure that works by a single impact that causes the diaphragm to start oscillating at its resonance frequency.[59] This device allows for operation with pressure as the input, where the cantilever does not. Wang and Ko later developed a device utilizing PVDF and polydimethylsiloxane (PDMS) that harvested energy through flow-induced vibrations with a diaphragm shape[60] (Figure 4b), and the device had a power output of 0.2 $\mu$W at a frequency of 26 Hz. Goldfarb and Jones investigated the efficiency of storing electrical energy within a piezoelectric material and found that a stacked set of PZT produce a much lower resonance frequency with higher efficiencies.[61] Xu et al. further developed this, investigating a larger, 300 layer stack.[62] The PZT-stack reached mechanical to electrical energy conversion efficiencies of 35%. More recently, to improve upon the single direction operation of basic cantilever shapes, Zhao et al. proposed a compact arc-shaped piezoelectric generator for harvesting wind energy from multiple directions[63] as shown in Figure 4c. It produced an output power of 1.73 mW at a wind speed of 17 m s$^{-1}$. Recently, Fan et al. developed a device to allow for harvesting energy from multiple directions as well as rotational and sway motions.[64] The device made use of four different piezoelectric cantilever beams, as
well as a ferromagnetic ball and a cylindrical track, which aided
in the ability to capture rotational and sway energy.

Other techniques also have emerged making use of the
piezoelectric energy harvesting mechanism. In the past decade
nanogenerators have become a well-studied topic. Wang and
Song developed single-wire generators (SWG) from piezo-
electric ZnO. These ZnO nanowires are grown through a
physical vapor deposition process. Later, SWGs were found
to produce harvestable electricity from the diaphragm of a rat
during breathing and the body motion of a live hamster. As
the technology matures, nanogenerators are emerging tech-
nology toward nanoenergy.

In addition, some other methods have been developed to
improve energy harvesting capabilities of piezoelectric EHs. For
example, mechanical bistability has been leveraged as a feasible
approach for amplifying forces applied to piezoelectric elements.
Specifically, bistable elements can move from one stable state to
a second in a snap-through action, resulting in larger deformations
for coupled piezoelectric elements. Means of integrating these
bistable structures with energy harvesters has been a topic of
interest recently. On the other hand, microstructures within
materials may also act to concentrate these stresses, and thus
increases mechanical to electrical energy efficiencies. Structure
design developments have also focused on improving electrical
outputs by increasing the concentration of stress within a piezo-
electric element. For example, Sharpe’s et al. improved upon 2D
beam structures for increasing concentrated stresses during
low frequency vibrations as shown in Figure 4d. Work in this
area will lead to improved devices, by smarter placement of
piezoelectric films on vibration-coupled structures. On the other
hand, great efforts have also been made to couple mechanical
energy harvesting through the piezoelectric effect with other
forms of energy harvesting including photovoltaics and pyro-
electrics. These hybrid technologies show great potential in
being able to meet energy requirements by utilizing multiple
energy sources in the environment.

Advances in multiple areas of research based on piezo-
electric materials will facilitate the development of devices with
increasing energy harvesting capabilities. Material improvements
will lead to a greater potential of electrical outputs from a given
stress. Meanwhile, system design improvements will contribute
to greater coupling between low resonant vibrations to highly
concentrated stresses, producing larger deformations and thus
greater electrical outputs. These designs will also increase the
range of operational frequencies with which they are able to har-
ness ambient energy. The lowering of operating frequencies will
result in a wider range of applications in ambient environment.
Many biological systems operate at frequencies lower than 5
Hz while many of the earlier developed vibration-based energy
harvesting devices were operated upward of 100 Hz. As these
devices’ outputs improve, strategies to harvest energy from mul-
tiple directions will become significant in increasing the range of
applications for these energy harvesting devices.

2.3. Electromagnetic EH

Based on the fundamental principle of Faraday’s Law of elec-
tromagnetic induction, electromagnetic energy harvesters are
designed using the relative motion of an electrical conductor
in a magnetic field, such that the motion of a magnetic field
relative to a conductive coil causes current to flow in the coil. A
typical electromagnetic energy harvester consists of a wire coil
attached to the mass connected to a spring (Figure 3b). When
the rigid housing vibrates, the mass moves with respect to the
rigid housing so that the coil moves through the field of the
permanent magnet, which in turn induces a voltage on the coil.

In earlier years, Beeby et al. designed an electromagnetic
energy harvester by using four magnets arranged on an etched
cantilever with a wound coil located within the moving magnetic
field. This harvester successfully delivered 30% of the power
supplied from an air compressor (frequency between 43 and
109 Hz with acceleration amplitudes between 0.19 and 3.7 m s−2)
to useful electrical power in the load. Kulah and Najafi proposed a different electromagnetic energy harvester struc-
ture with two resonators, the top of which is a plate suspended
with a soft spring to target the low resonance frequency, while
the bottom resonator was a cantilever beam corresponding to
higher resonance. Zhu’s research group designed a horizontal
tunable electromagnetic vibration-based microgenerator, where
an effective resonant frequency range from 67.6 to 98 Hz was
obtained using variable axial loads from a horizontal magnetic
force applied to the cantilever beam as shown in Figure 5a.

In addition, a detailed mathematical model for an electromag-
netic energy harvesting architecture was proposed to estimate the energy generated by the architecture by computing the
static and dynamic magnetic and electric fields. Later
Marin et al. improved the electromagnetic energy harvester
structure (Figure 5b) by using an additional pair of magnets
(which they referred to as a “double cell”) to create a secondary
air gap, or cell, for a second coil to vibrate within, and observed
a 23% enhancement in output with minor increase in volume.
This “double cell” harvester was then further developed by using
four “double cells” with varying resonance frequencies incorpo-
rated in the electromagnetic energy harvesting system. It was
found that the double cell array could generate a similar mag-
nitude of power to a single cell but provided three times larger
bandwidth. A multifrequency vibration-based micro-electro-
mechanical system (MEMS) electromagnetic energy harvesting
device was presented with a permanent magnet and a circu-
lar suspension structure on a MEMS EH chip. This energy har-
vester can vibrate out-of-plane (mode I), in torsion (mode II/III)
and in-plane (mode IV/V), corresponding to three resonant
frequency of 840, 1070, and 1490 Hz, respectively.

To couple with the electromagnetic generators for applica-
tions, a nonlinear energy extraction circuit (synchronized mag-
netric flux extraction) is used to enable the rectification and the
amplification of the voltages produced by an electromagnetic
energy harvester. More recently, an electromagnetic energy
harvester with a magnetic mass moving inside a frame-carrying
coil was designed as shown in Figure 5c. Their experiments
showed that the power output increased by ten times at 10 Hz
compared to the conventional energy harvester in which the
mass is directly connected to a vibrating frame using a spring
suspension.

Furthermore, nonlinear energy harvesting with a large band-
width has attracted more attention, since linear energy har-
vesters are normally limited and application specific due to
the random and various ambient vibration sources. A design of an electromagnetic vibration energy harvester without mechanical spring was presented\[80\] by using a structure with repelled permanent magnets, which provided useful nonlinear stiffness for the vibration energy harvester. The results showed that the nonlinear stiffness and power feedback would affect the operation of electromagnetic vibration energy harvester. In addition, Kucab et al.\[81\] compared the electrical response of an electromagnetic device working in both the linear and nonlinear domains. Their results showed that in nonlinear domain the device can produce a power output of 95 mW, while a power of only 80 mW was obtained in the linear domain. In addition, rotational electromagnetic motors, especially in large scale applications, such as building structures, have been adopted in VEH by transferring the linear motion of vibration into rotation\[82,83\].

In general, electromagnetic energy harvesters are primarily suitable for macroscale systems due to the scaling and design limitations imposed by MEMS fabrication processes. However, recent effort by using MEMS cantilever arrays\[84\] and microfabricated coils\[79\] have drawn great attention and shown promise for MEMS electromagnetic energy harvesting applications.

2.4. Electrostatic EH

The basic principle for electrostatic vibration-based energy harvesting is Coulomb’s Law. Electrostatic energy harvesters work through changes in capacitance of two parallel plate capacitors, typically electrically isolated by air, vacuum, or an insulator.\[10\] The attractive forces of these two oppositely charged parts changes with gap distance. Therefore, by changing the capacitance of vibration-dependent conductors, the mechanical energy from the vibrations can be converted into electrical energy as illustrated for a simple parallel plate capacitor shown in Figure 3c. A more detailed description of this approach is given by Meninger et al.,\[85\] where a hybrid technique which employs a parasitic capacitance to increase the power output is proposed.

The reported electrostatic energy harvesters in the literature make use of changes in gap distances in multiple ways. Typical designs make use of comb drives and the changes in capacitance are driven by a vibration source.\[86\] Figure 6a represents the typical schematics of an electrostatic based energy harvester. There are three most commonly studied designs for vibration-based electrostatic energy harvesters. In-plane overlap electrostatic designs, as shown in Figure 6a (top), make use of a change in capacitance caused by overlaps in the teeth of
the comb drive as it vibrates in the plane of the device. These devices often utilize mechanical stops to prevent device damage due to contact stiction. Gap overlap devices are subject to both rotation and tilt due to the applied vibration which can severely damage the comb drives. In-plane gap closing electrostatic generators, as shown in Figure 6a (middle), are very similar to the previously mentioned overlap designs, but actuation occurs perpendicular to but within the same plane as the gap overlap. The change in capacitance is caused by changes between the gap between the comb drive teeth. Mechanical stops are also required to avoid damaging stiction. These devices can also have some rotation and tilts that cause damage but not to the same extent as the in-plane overlap devices. Out-of-plane gap closing, as shown in Figure 6a (bottom), has the largest potential maximum capacitance, but has issues involving adhesion of the two capacitance plates due to surface interactions. Damping and stiction have a much larger effect, placement within a vacuum can improve this and drastically increase the power generation. On the other hand, the harvesting energy through electrostatic devices can be either charge or voltage constrained systems. In a voltage constrained system the variation in capacitance causes an increase in charge, while in a charge constrained system the variation causes an increase in voltage.

Recent work on electrostatic energy harvesters includes Basset’s MEMS based design as shown in Figure 6b, which achieved 61 nW at an input frequency of 250 Hz without the use of an electret layer. Later this research group further developed a MEMS based design that had an increased bandwidth of 30% with a power density of 2 µW cm⁻² at an input frequency of 140–160 Hz. The design made use of in-plane gap closing methods with drive combs. In addition, Naruse et al. developed a method that utilized long range movements at low frequency to harvest energy at frequency closer to human motions. The advantage of this design is that it allows for a controlled gap (38–57 µm), between the electrodes and long-range movements (15 mm). The microball bearings roll to keep separation gap controlled and constant as shown in Figure 6c. However, there is severe energy loss due to edge collisions of the device, and thus needed further refinement. The reported power output was 40 µW at an input frequency of 2 Hz.

In literature, other high frequency devices have been extensively investigated, since targeting lower resonance frequency is a challenge for a typical electrostatic EH system. One example is an electrostatic EH device (Figure 6d) with two capacitors attached to the same proof mass, so the capacitance changes are complementary in manner, produced 3.5 µW at resonance of 1300–1480 Hz for five different devices. More recently, Zhang et al. designed a dual resonant electrostatic energy harvester. The design made use of two cantilever beams with proof masses that had different resonance frequencies. This allowed for a broadened bandwidth of 30% of the central

Figure 6. Examples of electrostatic energy harvesters. a) The three most commonly used types of electrostatic energy harvesters with the relative movements of the interdigitated electrodes. Reproduced with permission. Copyright 2002, ASME. Top: in-plane overlap; middle: in-plane gap closing; bottom: out-of-plane gap closing. b) An electret-free silicon electrostatic energy harvester that was designed for batch fabrication. Reproduced with permission. Copyright 2009, IOP Publishing. c) A structure that makes use of microball bearings to target low frequency vibrations. Reproduced with permission. Copyright 2009, IOP Publishing. d) A microscopic close up of an electrostatic EH design with interdigitated comb electrodes. Reproduced with permission. Copyright 2009, IOP Publishing. e) An EH device that makes use of a CYTOP electret film that was able to produce a broad frequency bandwidth and a high power density Reproduced with permission. Copyright 2018, Elsevier.
frequency because of the collision coupling effects between the two masses. The power output ranged from 6.2–9.8 \( \mu \)W from an input frequency of 36.3–48.3 Hz. Later, Zhang et al. further developed an out-of-plane gap closing MEMS device that made use of CYTOP electret material\(^{[93]}\) as shown in Figure 6e. The device achieved 4.95 \( \mu \)W at a frequency of 136 Hz, and it also had a wide range of frequencies ranging from 160 \( \pm \) 12.5 Hz.

Electrostatic energy harvesters have advantages including their ease of fabrication and integration with MEMS; however, they have other issues. One of the primary disadvantages is that it requires some base input of energy to produce; this can be dealt with by adding an electret layer, which acts a permanent charge buried within a dielectric layer.\(^{[94]}\) Another disadvantage of electrostatic EH is that off-axis vibrations can cause severe damage via rotation of the comb drives, resulting collisions between capacitance plates. These devices work most optimally in a small frequency range at or near their resonance and in a single direction of the applied vibration. Furthermore, it is difficult to match the resonant frequency of a device with the input frequency as small design errors can shift the central frequency, and the narrow frequency band leaves little room for error.\(^{[92]}\) Since most applications require the ability to convert mechanical energy in the form of vibrations from a wide range of frequencies,\(^{[88]}\) narrow frequency bandwidth leaves little room for error in device fabrication and in changes in excitation vibrations.

### 2.5. Triboelectric EH

Triboelectric effect where opposite charges are created and accumulated at the surfaces of two contacting objects is ubiquitous in everyday life, but people rarely relate it to energy harvesting until Wang and his co-workers designed and fabricated the first flexible triboelectric generator in 2012 (Figure 7a).\(^{[28]}\) The fundamental principle of the triboelectric generator lies on the migration of electrical charges between two materials.\(^{[26]}\) When two materials are in contact, charges (e.g., electrons, ions, and/or molecules) from one can transfer to the other to balance their electrochemical potential. When materials are separating from each other, some atoms are inclined to send extra electrons away and some tend to keep them. Thus, an electrical potential difference is created between the two material and the triboelectric charges on dielectric surfaces drive to form a current of electrons to equalize the electrical potential difference. The current \( I \) can be expressed using this Equation (5)

\[
I = C \frac{\partial V}{\partial t} + V \frac{\partial C}{\partial t}
\]  

where \( V \) is the voltage across the electrode, \( C \) is the capacitance of the system, and \( t \) is the time. The first term describes the change in the potential across the electrodes due to electrostatically induced charges and the second term is the variation in the capacitance. Triboelectric nanogenerators (TENG) are developed based on this mechanism and generally have four modes including contact-separation, sliding, freestanding and single-electrode modes as depicted in Figure 7b. In addition, the systematic study of the theory behind TENG’s working mechanism for these modes are presented in Niu et al.’s work.\(^{[95–97]}\)

TENG is a simple yet extremely capable device for scavenging vibration based energy. Vibration simply implies repetitive relative physical motions which provide the mechanical motion for each of the four modes of TENG to work. Therefore, researchers have devoted a considerable amount of work in improving the energy conversion efficiency and creating innovative structures for different vibration based applications. To improve the energy conversion efficiencies, Xie et al. designed a TENG that uses the freestanding mode with a triboelectric-layer structure with grating units.\(^{[98]}\) Alternating currents are generated while the grating segments sweep across multiple electrodes. This design showed great stability and superb conversion efficiency as high as 85% at relatively low working frequencies. Moreover, Tang et al. realized developed a liquid-metal-based TENG to create a liquid-solid interface that greatly increased the contacting area.\(^{[99]}\) In that work, the energy density was demonstrated to be 133 kW m\(^{-3}\), and the instantaneous energy conversion efficiency reached 70.6%.

In addition to the effort in achieving high conversion efficiency, researchers have also developed many innovative TENG structures for different applications. A triple-cantilever based device, one of the first TENGs was specifically designed for harvesting ambient vibrational energy.\(^{[97]}\) The device can produce an open circuit voltage of 101 V and a short circuit current of 55.7 \( \mu \)A. Moreover, TENG is a versatile device that can harvest energy from a variety of motions. For example, typing or pressing button on machines such as computers produce a large amount of energy that would be otherwise wasted if not collected. Researchers have used the contact-separation mode to design TENGs for harvesting typing energy to light up LEDs or power small electronics.\(^{[100,101]}\) For example, a soft, thin, water resistant key board cover is developed using the materials and mechanisms depicted in Figure 7c.\(^{[100]}\)

Human body motion provides ample mechanical energy and the problem is how to collect it effectively and convert it to electricity to power wearable electronics, as it is a growing market in recent years. TENG becomes a solution owing to its energy conversion ability, flexibility,\(^{[102]}\) and biocompatibility.\(^{[103]}\) For example, Yang et al.\(^{[104]}\) created a TENG using a hybridization of the contact-separation and sliding mode with nanowires and nanopores that can generate a peak power density of 30.7 W m\(^{-2}\) in a short-circuit (Figure 7d). Another TENG that also used a hybridization mode of vertical contact-separation and in-plane sliding along with a spring assembly was developed.\(^{[105]}\) This newly designed TENG structure can capture the vibrational energy not only from arbitrary in-plane directions but also from out-of-plane directions. They also mounted the device on a human leg to harvest the vibration energy from human walking at different walking speed and showed a voltage output up to around 120 V. More recently, a TENG fabric that is wearable using 3D orthogonal woven technique was created (Figure 7e) and showed a promising peak power density of 263.36 mW m\(^{-2}\).\(^{[106]}\) This device is also working under contact-separation mode but provide a soft textile owing to the 3D woven yarn. Furthermore, researchers
Figure 7. Triboelectric nanogenerators. a) The first triboelectric generator and its working mechanism. Reproduced with permission.\cite{28} Copyright 2012, AIP Publishing. b) Four modes of the working mechanism of TENG: contact-separation mode, contact-sliding mode, single electrode mode and freestanding model. Reproduced with permission.\cite{26} Copyright 2014, Royal Society of Chemistry. c) The mechanism and materials of a TENG that collect typing energy from a computer keyboard. Reproduced with permission.\cite{100} Copyright 2016, American Chemical Society. d) A TENG that uses both contact-separation and sliding mode to scavenge vibrational energy from multi-directions. Reproduced with permission.\cite{98} Copyright 2013, American Chemical Society. e) The schematic (top) and picture of a wearable TENG fabric using 3D orthogonal woven technique to collect energy from human body motions. Reproduced with permission.\cite{99} Copyright 2017, John Wiley and Sons. f) A ball-shape TENG that can harvester energy in full space using both contact-separation and sliding mechanisms. Reproduced with permission.\cite{101} Copyright 2014, John Wiley and Sons. g) A platform built based on triboelectric mechanism that is both a vibrational energy harvester and a motion sensor. Reproduced with permission.\cite{102} Copyright 2013, John Wiley and Sons.
presented the triboelectric based EH’s promising usages in self-powered electronics. For example, efforts have been made on coupling electromagnetic–triboelectric effect for hybrid EH devices in effective energy storage,[106] self-powered wearable electronics,[108] and self-powered temperature–humidity sensors.[109]

In order to harvest energy in full space (independent of the vibration direction), researchers have innovated spherical 3D TENGs with single or multiple electrodes.[110,111] Zhang and co-workers[112] designed a single electrode-based TENG working at a hybridization of both the contact-separation mode and sliding mode. A free-to-move polyfluoroalkoxy (PFA) ball is contained in a bigger outer transparent shell (Figure 7f). However, single-electrode TENG may be subjected to limited output current, Yang et al.[113] therefore designed a 3D integrated multilayered TENG. The TENG is then equipped inside ball that can be held by hand. This device yielded a 303 V voltage and 1.14 mA current in an open-circuit setup. It is worth mentioning that these two ball-shape TENGs have promising future for large-scale energy harvesting when a large amount of them are woven into webs for collecting ocean wave energy, which is so called “blue energy.”[26] Furthermore, since TENG can convert mechanical motion into electricity, it can be used as an energy harvester or a sensor to detect mechanical motions ranging from body motion to sound wave. Researchers have built TENG devices that integrate both energy harvesting and sensing capabilities. Examples include a transparent and flexible TENG-based self-powered pressure sensor,[112] vibration sensors,[99,113,114] (Figure 7g), an acceleration sensor,[116] a strain sensor,[117] a liquid volume sensor for self-powered lab-on-chip applications,[118] a pressure sensor,[119] and a glucose sensor[120] for biomedical applications, motion sensors,[106,119] and a sound recorder.[120] All these sensors are based on the same basic mechanism of a TENG and hence can be used for energy harvesting in corresponding applications.

2.6. Summary of the Four VEH Mechanisms

The four primary vibration-based energy harvesting mechanisms including piezoelectric, electromagnetic and electrostatic energy harvesting have been discussed and a summary of discussed EH devices based on those four VEH mechanisms is listed in Table 1. Compared to other transduction mechanisms, the piezoelectric energy harvesting approach can convert mechanical vibrations directly to the electrical energy without external source to initiate the energy conversion. Scaling of the power with volume also favors the piezoelectric energy harvesters in smaller scales. However, the challenges of implementing the piezoelectric approach include the difficulties of integration with MEMS processing techniques,[121] and the fact that the piezoelectric coupling is greatly reduced when the piezoelectric films are integrated within standard MEMS fabrication processes, which limits overall performance of small-scale piezoelectric energy harvesters. In addition, the efficiency for the piezoelectric energy harvesting is ultimately limited by the piezoelectric properties of materials employed, and the output impedance of piezoelectric energy harvesters are typically very high (>100 kΩ), which corresponds to low electrical currents although the piezoelectric method is capable of producing relatively high output voltages.[10]

For electromagnetic energy harvesting, according to the previous research, it may not favorably scale down to the micro size because the power is limited by the interactions of the coils and magnets as the scale is reduced.[97] This is because that the mechanical energy in electromagnetic devices is associated with the movement of a mass through a certain distance, working against a damping force. It is clear that the mechanical energy will decrease with the dimensions as both the mass of the moving object and the distances moved are decreased. The primary advantage of electromagnetic energy harvesters is their reliable performance, because they only rely on the relative velocity and the change in the magnetic flux in order to generate electricity and the system can be easily designed without the necessity of mechanical contact. In addition, no separate voltage source is needed for electromagnetic energy harvesters to get the harvesting process started as in electrostatic conversion. A theoretical maximum energy density around 300–400 cm\(^{-3}\) can be achieved based on Roundy’s calculation,[122] which is similar to that found for the piezoelectric energy harvesting.

For the method of electrostatic energy harvesting, the obvious significant advantage is the potential for facile integration with microelectronics based on the process compatibility with existing MEMS technology. However, the primary disadvantage is that a separate voltage source is necessary in order to initiate the energy conversion process. In addition, the electrostatic EH has a reliability concern due to possible mechanical contact and electrical short-circuit, and those issues will also affect the reliability and performance of energy harvesters based on this energy harvesting mechanism.

For triboelectric energy harvesting, TENG as an emerging device in recent years that has attracted many researchers’ attention certainly has its unparalleled advantages over other the energy harvesters. Since the device is based on triboelectric effect which can almost occur, to different extent, between any two materials, there is abundant choices of material that can be used for building the device. This great material selection allows the device to be used in a large range of environment such as in a living biological setting when biocompatible material is used. Also, TENG can not only be scaled down to microscale to provide power source for miniature electronics, but also it has been demonstrated to harvest the energy from much larger sources such as from flowing river, rains and ocean waves. However, TENG tends to have a lower durability and stability as it relies on the physical contact between two surfaces. Also, the device performance is too dependent on the environment such as humidity.

The advantages and disadvantages of each type of energy harvesting mechanism discussed above are also summarized in Table 2. Both piezoelectric and electrostatic energy harvesters are compatible with MEMS, therefore, they can be used in micro/nano scale systems while electromagnetic energy harvesters are more suitable for macroscale systems. Based on Roundy’s analysis,[121] piezoelectric and electromagnetic energy harvesting both have similar theoretical maximum energy densities around 300–400 cm\(^{-3}\), while the electrostatic energy harvesting has a much smaller maximum energy density of 44 cm\(^{-3}\).
3. Geometry Based Frequency Matching Techniques for VEH

Vibrations offer attractive solutions for ambient energy harvesting due to their higher energy densities. Based on the generic spring–mass–damper model of vibration-based energy harvesting discussed in Section 2, in order to maximize the use of the energy harvesters for a particular application, the structure frequency of the energy harvesting device is designed to match the source frequency ($\omega_{\text{struc}} = \omega_s$). Due to

<table>
<thead>
<tr>
<th>Reference</th>
<th>Power [µW]</th>
<th>Frequency [Hz]</th>
<th>Acceleration [m/s²]/force [N]</th>
<th>Volume [mm³]</th>
<th>Power density [µW mm⁻³]</th>
</tr>
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<tbody>
<tr>
<td>Piezoelectric energy harvesting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Glynn-Jones et al.[54]</td>
<td>3</td>
<td>80.1</td>
<td>–</td>
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<td>0.04⁰</td>
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<td>Roundy et al.[9]</td>
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<td>100</td>
<td>2.5</td>
<td>1000</td>
<td>0.252</td>
</tr>
<tr>
<td>Li et al.[37]</td>
<td>0.35</td>
<td>16</td>
<td>9.81</td>
<td>347</td>
<td>0.001</td>
</tr>
<tr>
<td>Bai et al.[38]</td>
<td>50/20 Hand motions/ head motions</td>
<td>–</td>
<td>–</td>
<td>1680</td>
<td>h,b</td>
</tr>
<tr>
<td>Xu et al.[60]</td>
<td>347000</td>
<td>1204</td>
<td>22.15 N</td>
<td>1750</td>
<td>198.3</td>
</tr>
<tr>
<td>Zhao et al.[83]</td>
<td>1730</td>
<td>wind</td>
<td>wind</td>
<td>2758</td>
<td>0.627</td>
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<td>Cao et al.[22]</td>
<td>8.55</td>
<td>69.8</td>
<td>15.7</td>
<td>229</td>
<td>h,k</td>
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<td>Ren et al.[23]</td>
<td>1400</td>
<td>500</td>
<td>0.55 N</td>
<td>74.48</td>
<td>18.79⁰</td>
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<td>46</td>
<td>52</td>
<td>0.59</td>
<td>150</td>
<td>0.307</td>
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<td>25</td>
<td>–</td>
<td>200⁰</td>
<td>1.985 × 10⁻³⁰</td>
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<td>61.6–156.6</td>
<td>67.6–98</td>
<td>0.59</td>
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<td>19000</td>
<td>168.58</td>
<td>–</td>
<td>111000</td>
<td>0.171</td>
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<td>Marín et al.[15]</td>
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<td>50</td>
<td>1.96</td>
<td>1179000</td>
<td>0.0216/0.0167</td>
</tr>
<tr>
<td>Liu et al.[26]</td>
<td>5.5 × 10⁻³/0.5 × 10⁻³/ 4.1 × 10⁻³</td>
<td>840/1070/1490</td>
<td>9.81</td>
<td>35</td>
<td>0.157 × 10⁻³/0.014 × 10⁻³/ 0.117 × 10⁻³</td>
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<tr>
<td>Arroyo et al.[37]</td>
<td>1600</td>
<td>100</td>
<td>9.81</td>
<td>10000</td>
<td>0.16</td>
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<td>Haroun et al.[25]</td>
<td>350000</td>
<td>10</td>
<td>–</td>
<td>16000⁰</td>
<td>2.1875</td>
</tr>
<tr>
<td>Hadas and Ondrusek[90]</td>
<td>150</td>
<td>h</td>
<td>0.02</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Kucab et al.[81]</td>
<td>95000</td>
<td>26.6</td>
<td>98.1</td>
<td>17000</td>
<td>h</td>
</tr>
<tr>
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<td></td>
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<td></td>
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<td>250</td>
<td>2.45</td>
<td>25.08⁰</td>
<td>0.243 × 10⁻³⁰</td>
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<td>6.2–9.8</td>
<td>36.3–48.3</td>
<td>9.3</td>
<td>3000</td>
<td>2.067 × 10⁻³/3.267 × 10⁻¹⁰</td>
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<td>9.81</td>
<td>42</td>
<td>0.052</td>
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<td>40</td>
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<td>3.92</td>
<td>288</td>
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<td>3.5</td>
<td>1330–1480</td>
<td>127.53</td>
<td>200</td>
<td>0.0175</td>
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<td>Zhang et al.[93]</td>
<td>4.95</td>
<td>136</td>
<td>.8829</td>
<td>187</td>
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<td>Triboelectric energy harvesting</td>
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<td>Fan et al.[28]</td>
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<td>–</td>
<td>294</td>
<td>10.4</td>
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<td>Li et al.[100]</td>
<td>–</td>
<td>0.5–5</td>
<td>1.84–3.33 N</td>
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<td>300 mW m⁻²</td>
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<td>Jiang et al.[101]</td>
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<td>1</td>
<td>–</td>
<td>20</td>
<td>21.6 mW m⁻²</td>
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<td>Yang et al.[106]</td>
<td>=1.2 × 10⁴</td>
<td>h</td>
<td>2 kg</td>
<td>77900</td>
<td>15.4</td>
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<td>Yang et al.[105]</td>
<td>1180</td>
<td>0–140</td>
<td>6</td>
<td>23550</td>
<td>1.45 W m⁻²</td>
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<tr>
<td>Dong et al.[106]</td>
<td>59.26</td>
<td>h</td>
<td>0.5–5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Zhang et al.[110]</td>
<td>128</td>
<td>2–100</td>
<td>–</td>
<td>12.6 cm²</td>
<td>0.1016⁰</td>
</tr>
<tr>
<td>Yang et al.[111]</td>
<td>12 × 10⁶</td>
<td>h</td>
<td>2–54</td>
<td>–</td>
<td>232000</td>
</tr>
<tr>
<td>Chen et al.[112]</td>
<td>2810</td>
<td>h</td>
<td>2–200</td>
<td>38.7 cm²</td>
<td>726.1 mW m⁻²</td>
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<tr>
<td>Fan et al.[120]</td>
<td>–</td>
<td>0–1200</td>
<td>–</td>
<td>–</td>
<td>0.968</td>
</tr>
</tbody>
</table>

a)Estimated data from the reference; ḗThe volumes of the proof mass are included in the total volume calculations.

Table 1. Summary of reported vibration energy harvesters based on piezoelectric, electromagnetic, electrostatic, and triboelectric harvesting mechanisms.
Therefore, it is straightforward to plot the normalized frequency ratio of \( f' \) as a function of mass change ratio of \( \Delta m/m_{\text{eff}} \) based on Equation (7) as shown in Figure 8a. In practical terms, an effective way to implement frequency tuning for vibration-based energy harvesters is to change the system effective stiffness \( k_{\text{eff}} \) (Equation 6). This can be pursued via two approaches: one is to change the geometries of the structure and thus to adjust the structure effective stiffness, and the other way is to add an additional stiffness within the vibrating system.

Based on a commonly used, bilayer (PZT and silicon layers) laminated composite cantilever with one end clamped and the other end with a proof mass configuration, the most practical tuning approach is to change the beam effective length among the various geometric parameters. By defining a modified beam length as \( L' = L + \Delta L \), the normalized ratio of the effective tuned frequency \( f' \) to the original untuned frequency \( f \) can be written as a function of different beam lengths, such that

\[
f' = \frac{L' - \Delta L}{L' + \Delta L} \cdot \left[ \frac{m_{\text{eff}} + \Delta m}{m_{\text{eff}}} \right] \left[ \frac{m_{\text{eff}} + \Delta m}{m_{\text{eff}}} \right] \left[ \frac{1}{m_{\text{eff}}} \right] \left[ \frac{1}{m_{\text{eff}}} \right]
\]

(8)

Therefore, a normalized resonant frequency of a cantilever beam with a variation of \( \Delta L/L \) for the beam length is shown in Figure 8b. It can be concluded from Figure 8b that a positive variation of \( \Delta L/L \) defines a longer cantilever beam, corresponding to a decreased resonant frequency \( f' < f \), while a shorter beam \( -1 < \Delta L/L < 0 \) results in an increase of the resonant frequency of energy harvesters \( f' > f \).
In addition to changing the geometries of the structure, the most direct way to alter the system’s effective stiffness is to incorporate an additional stiffness to the system as shown in Figure 8c. The added stiffness $k_{\text{add}}$ can be represented by a parallel spring to the original stiffness $k_{\text{struc}}$; therefore, the system’s effective stiffness and corresponding tuned resonant frequency of vibration-based energy harvesters can be written as

$$k_{\text{eff}} = k_{\text{struc}} + k_{\text{add}}$$ (9)

$$f' = \frac{1}{2\pi} \sqrt{\frac{k_{\text{struc}} + k_{\text{add}}}{m_{\text{eff}}}}$$ (10)

Then the normalized effective tuned frequency $f'$ to the original untuned frequency $f$ as a function of normalized stiffness ratio $\alpha = k_{\text{add}}/k_{\text{struc}}$ can be written as

$$f' = \frac{f}{f} = \sqrt{\frac{k_{\text{struc}} + k_{\text{add}}}{k_{\text{struc}}}} = \sqrt{1 + \alpha}$$ (11)

Given the normalized frequency ratio above, it is straightforward to show the effect of the normalized stiffness on the frequency. As shown in Figure 8d, the tuned frequency could be as large as 330% of the untuned frequency of energy harvesting if an additional stiffness (where $k_{\text{add}} = 10k_{\text{struc}}$) is added to the system. Note that the normalized stiffness factor is always larger than $-1$ ($k_{\text{add}}/k_{\text{struc}} > -1$), corresponding to a positive normalized resonant frequency. For a positive normalized stiffness factor ($k_{\text{add}}/k_{\text{struc}} > 0$), the added stiffness will induce a stiffening effect, and thus resulting in an increase of the tuning frequencies ($f'/f > 1$), while a negative normalized stiffness factor ($k_{\text{add}}/k_{\text{struc}} < 0$) contributes to a softening effect and a decrease of the resonant frequencies of the energy harvesting device ($0 < f'/f < 1$).

On the other hand, various tuning mechanisms developed specifically for the membrane-based structure, which is another important vibration structure used in energy harvesting, will be considered. For the membrane-based energy harvesters, the frequency of the first fundamental frequency for a membrane with central mass-loaded is given

$$f = \frac{1}{2\pi} \sqrt{\frac{2\pi T}{m \ln \left( \frac{a}{b} \right)}}$$ (12)

where the mass of the membrane $M$ is assumed small compared to the added mass $m$ and hence neglected. Based on
Equation (12), three factors that affect the mass-loaded circular membrane frequency include the membrane tension, the mass of the added mass, and the radius ratio of the membrane to the added mass. Because it is difficult to change the added mass or the geometry (radius) of both membrane and added mass during device operation, changing the membrane tension appears to be the most practical approach to tune the resonant frequency of membrane-based energy harvesters.

3.2. Tuning Approaches for Beam Configuration

By using the principle of tuning methods discussed above, the results of reported tunable cantilever geometry-based energy harvesters are discussed here. A patent by Gieras et al.\textsuperscript{[127]} presented a tunable vibration-based energy harvester with an effective flexible length $L$ of the cantilever beam by using a stabilizer positioned by an actuator. In this design, the system had a controller module consisting of an accelerometer for sensing frequencies of applied vibrations and a processor for determining the target effective length of the cantilever beam. In addition, the effective beam length of the cantilever geometry-based energy harvesting structure can be adjusted by moving the center of gravity of the tip mass. Wu et al.\textsuperscript{[128]} proposed a structure for a piezoelectric energy harvester, where the position of the center of mass of the proof mass depends on the positions of the fixed part and movable part. By using a length of 30 mm for the movable part in that work, the tuned frequency was obtained between 130 and 180 Hz.\textsuperscript{[129]}

From the geometry perspective, topological optimization strategies have been employed in vibration energy harvesting.\textsuperscript{[129–132]} especially it can also be used to implement the frequency tuning. For instance, the geometries of the elastic beam and the tip mass were optimized theoretically for a bimorph energy harvester.\textsuperscript{[133]} Another example of mass tuning for power optimization was for sensing living cells or weighing biomolecules, single cells, and single nanoparticles, they illustrated the resonant frequency tuning method by changing geometry of the structure.\textsuperscript{(i.e., the shape of the cantilever and the added mass). By changing the effective stiffness of system, the frequency tuning of an energy harvester can be implemented using magnetic, piezoelectric, and electrostatic methods. For instance, the added stiffness can be applied via an additional magnetic force on the energy harvesting structure. Challa et al.\textsuperscript{[137]} presented a resonance frequency tunable energy harvesting approach which applied a vertical magnetic force perpendicular to the cantilever beam and was able to achieve tuning to $\pm 20\%$ of the unturned frequency based on the mode (attractive or repulsive) of the magnetic force. In addition, Zhu et al.\textsuperscript{[122]} designed a horizontal tunable electromagnetic vibration-based microgenerator, where an effective resonant frequency range from 67.6 to 98 Hz was obtained using an axial tensile force. Recently, the 2D resonant frequency tuning approach was developed by the author, which extended these approaches by positioning of the magnets in 2D space\textsuperscript{[138]} as shown in Figure 9a. The tuning model was based on the effective stiffness theory, where the effective resonant frequency of the system was related to two additional stiffnesses (transverse stiffness and axial stiffness) added to the system. The results showed that the transverse stiffness term was in general significantly larger than the axial stiffness contribution, suggesting that from a tuning perspective it may be possible to use the transverse and axial stiffness contributions for coarse and fine frequency tuning, respectively. Such a 2D tuning method may be useful, in particular, for applications where space constraints impact the available design space of the energy harvester.

Other than using the magnetic stiffness methods, Peters et al.\textsuperscript{[139]} proposed a tunable resonator for energy harvesting by changing the structure’s stiffness using two piezoelectric actuators, one of which was clamped while the other free actuator could swing around the axis of rotation due to the inverse piezoelectric effect when an excitation was applied to the clamped actuator. By changing the torsional piezoelectric stiffness of the resonator via the applied voltage of $\pm 5$ V, a resonant frequency tuning range of 66 to 89 Hz was obtained with the untuned frequency of 78 Hz. Another piezoelectric energy harvester tuning method was proposed by Wischke et al.\textsuperscript{[140]} by using a cantilever beam with two PZT layers bonded with a polymer layer. By applying an electrical voltage on the piezoelectric layer, the stiffness of the structure is changed because of the tensile stress applied to the beam, and a feasible frequency tuning range of 25 Hz within voltage from -65 to +130 V was suggested.

The other way to implement resonance tuning is by using an electrostatic method as has been proposed and designed by many researchers. Scheibner et al.\textsuperscript{[141]} designed a tunable resonator structure with a cantilever-based comb structure, whose stiffness varied by induced electrostatic forces from the tuning voltage. In addition, frequency tunable comb resonators with 186 pairs of curved finger was designed by Lee et al.\textsuperscript{[142]} as shown in Figure 9b. The resonant frequency was found to decrease by 55% from the initial frequency of 19 kHz under a bias voltage of 150 V while the corresponding effective stiffness decreased by 80% from the initial value of 2.64 N m$^{-1}$. By using this curved comb design, a constant electrostatic stiffness corresponding to a linear electrostatic force was obtained under a control voltage.

On the other hand, the approach of using multiple harvesting mechanisms that together comprise the complete energy harvesting unit requires that each of these individual harvesters be designed to have a different resonance frequency, so that taken together these units span the desired target frequency bandwidth. The idea was patented by the Boeing Company for the multifrequency piezoelectric energy harvester.\textsuperscript{[143]}
The piezoelectric material was attached to each beam, therefore, the vibrations covering a broad band of frequencies resulted in the vibration of multiple beams to simultaneously contribute to the electrical energy conversion. By using multiple harvesting mechanisms, Berkcan et al. later proposed a structure with multiple cantilever beams, each of which is connected to the resilient common backbone at a location along the medial portion of the cantilevered beam in order to expand the bandwidth of energy harvester. Gao et al. presented a piezoelectric energy harvesting configuration with plural bendable substrates, each of which has a different span width, corresponding to an overall increased frequency range of energy harvester. In that design, vibration collisions between the bendable substrate and the housing induce the forces on the piezoelectric element in order to generate the electrical energy. In addition, Xue et al. designed a broadband piezoelectric harvester by integrating multiple piezoelectric bimorphs with different frequencies, and it was found that the operating frequency of the energy harvesting devices can be tailored by the connection patterns (i.e., in series and in parallel) among piezoelectric beams. More recently, Lee and Kim designed a piezoelectric energy harvesting array, which could be connected to each energy harvester in parallel or in series to tune the resonant frequencies of energy harvesting device.

In addition, nonlinear energy harvesting is another important approach to target a larger bandwidth. There are two types of nonlinear mechanisms for energy harvesting devices. The first one is to utilize a hardening-type stiffness element. The theory for this type of nonlinear energy harvesting is formulated using Duffing’s equation including the spring force as the combination of both linear component and nonlinear component. Numerical and analytical studies showed that a nonlinear energy harvester with a hardening spring has a larger bandwidth over which power can be harvested due to the shift in the resonance frequency. Based on Ramlan et al.’s analysis and the comparison with Zhu’s results, the bandwidth of the nonlinear hardening system depends on the damping ratio, the nonlinearity, and the input acceleration. Many researchers have explored and designed nonlinear energy harvesters. For instance, Burrow and Clare designed a nonlinear energy harvester, where the magnetic reluctance force resulted in the nonlinearity and the vibration of magnets caused a change in magnetic flux and hence inducing a voltage across the coil. Their results showed that the nonlinear system had a wider bandwidth than the linear energy harvester. For example, Zhang demonstrated a nonlinear oscillator, which also showed better performance compared to a linear oscillator in terms of the energy extracted from a generic wide spectrum vibration. Another example of hardening stiffness based nonlinear EH was proposed by Mann and Sims using the restoring forces between magnets. In that work two outer magnets were attached to a support, and a center magnet was placed between the two outer magnets with the magnetization direction oriented to repel the center magnet, suspending the center magnet by a nonlinear restoring magnetic force. It was found that at low excitation levels the frequency response of the system was similar to the response of a linear system; while at high excitation levels the peak response of the system was tuned away from the linear resonance with higher amplitude, suggesting a wider bandwidth based on the nonlinear response of the system.

For a nonlinear energy harvesting system with a hardening spring, it was concluded by Ramlan et al. that although it has a larger bandwidth due to the shift of resonance frequency, the maximum amount of power harvested by a nonlinear system (with a hardening stiffness) is the same as the maximum power by a linear system, irrespective of degree of the nonlinearity.
The second type of nonlinear mechanism employs a bistable nonlinear spring, which is also referred as a snap-through mechanism featuring rapidly moves the “seismic mass” between two stable states.\cite{148,153,154} From Ramlan et al.’s analysis, this bistable nonlinear mechanism results in a negative stiffness that steepens the gradient of the displacement response as a function of time and hence increases the maximum velocity. It was also found that the amount of power harvested by this type of nonlinear device was at most $\frac{4}{\pi}$ greater than that of the tuned linear device, provided the device produces a square wave output for given sinusoidal input.\cite{148} An example of a bistable oscillator was designed by Cottone et al.,\cite{155} where decreasing the distance between the external magnet and the tip magnet changes the potential from monostable to bistable. Specifically, when the external magnet was far away, the inverted pendulum behaved like a linear oscillator; however, when the distance difference is small enough, two new equilibrium positions appeared. In that work, the researchers demonstrated that this inverted pendulum could provide better performance compared to a linear oscillator in terms of the energy extracted from a generic wide spectrum vibration. Therefore, it can be concluded that the nonlinear energy harvesting has the potential to improve the system performance regarding the bandwidth. However, the nonlinear system design is quite complex depending on the interdependence of many parameters; moreover, higher order nonlinearities may require numerical solutions. A summary of reported tunable cantilever-based energy harvesters with the proposed tuning approaches are listed in Table 3.

### 3.3. Tuning Approaches for Membrane Configuration

In recent years, several studies have reported the potential tuning approaches for the membrane-based energy harvesting. For instance, Mo et al.\cite{156} presented a theoretical model for predicting the energy harvested by a PVDF circular membrane subjected to pressure fluctuations (Figure 10a). Based on the results of the simulated energy for a thin PVDF membrane\cite{10a} (bending neglected), the optimization of the energy generating performance was highly dependent on the ratio between the thickness and radius of the membrane, illustrating the mathematical relationship between those geometric parameters in order to maximize energy harvesting performance. Another reported membrane-based energy harvester was proposed by Palosaari et al.\cite{157} as shown in Figure 10b. The piezoelectric energy harvester consisted of an electrode coated PZT-5A membrane and a steel plate clamped with adjustable rings by screws. The prestress was adjusted with a linear spring by tuning the gap between the membrane and the spring cavity. As the results, the proposed energy harvester generated over 1.1 mJ of energy when applying a prestress of 17.6 and 22.5 N, however, only 0.456 mJ of energy can be produced without the prestress. Although a tunable membrane-based energy harvester was not specifically explored in that work, their experimental

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**Table 3.** Summary of reported typical tuning approaches for cantilever-based energy harvesters including resonance-based tuning and expanded bandwidth methods.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Frequency tuning methods</th>
<th>Untuned frequency [Hz]</th>
<th>Tuning range [Hz]</th>
<th>Tuning load (force/displacement)</th>
<th>Power output [µW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gieras et al.\cite{127}</td>
<td>Changing geometry</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Wu et al.\cite{128}</td>
<td>–</td>
<td>–</td>
<td>130–180</td>
<td>21 mm</td>
<td>–</td>
</tr>
<tr>
<td>Zhu et al.\cite{72}</td>
<td>Magnetic stiffness</td>
<td>45</td>
<td>67.6–98</td>
<td>3.8 mm</td>
<td>61.6–156.6</td>
</tr>
<tr>
<td>Challal et al.\cite{135}</td>
<td>26.2</td>
<td>22–32</td>
<td>–</td>
<td>3 cm</td>
<td>240–280</td>
</tr>
<tr>
<td>Dong et al.\cite{138}</td>
<td>61</td>
<td>51–87</td>
<td>–</td>
<td>12.7 mm (trans)</td>
<td>–</td>
</tr>
<tr>
<td>Peters et al.\cite{139}</td>
<td>Piezoelectric stiffness</td>
<td>78</td>
<td>66–89</td>
<td>–</td>
<td>5 V</td>
</tr>
<tr>
<td>Wischke et al.\cite{140}</td>
<td>299</td>
<td>750–300</td>
<td>–</td>
<td>–65 to 130 V</td>
<td>–</td>
</tr>
<tr>
<td>Scheibner et al.\cite{141}</td>
<td>Electrostatic stiffness</td>
<td>3.66k</td>
<td>1.4–3.66k</td>
<td>–</td>
<td>32.5 V</td>
</tr>
<tr>
<td>Lee et al.\cite{142}</td>
<td>19k</td>
<td>8.45–19k</td>
<td>–</td>
<td>150 V</td>
<td>–</td>
</tr>
</tbody>
</table>

**Expanding bandwidth methods**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Expanding bandwidth</th>
<th>Number of cantilevers</th>
<th>Tuning range [Hz]</th>
<th>Power [µW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkcan et al.\cite{144}</td>
<td>Multiple structures</td>
<td>4</td>
<td>100–900</td>
<td>–</td>
</tr>
<tr>
<td>Xue et al.\cite{146}</td>
<td></td>
<td>10</td>
<td>92–110</td>
<td>40–140</td>
</tr>
<tr>
<td>Lee and Kim\cite{147}</td>
<td></td>
<td>5</td>
<td>59.8–62.6</td>
<td>0.9–1.6</td>
</tr>
<tr>
<td>Burrow and Clare\cite{155}</td>
<td>Nonlinear (stiffness)</td>
<td>Better performance at excitation frequencies higher (lower) than resonant frequency, but complexity in design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mann and Sims\cite{152}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhang\cite{151}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cottone et al.\cite{155}</td>
<td>Nonlinear (bistable)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\footnote{Estimated data from the reference.}
results suggest that the pressure fluctuation could be a potential method used to tune the resonant frequency of membrane-based energy harvester to match the ambient vibrations for maximum power output.

On the other hand, multiple membrane structures and nonlinear membrane-based energy harvesting approaches are possible solutions to implement frequency matching from a bandwidth perspective. For example, a piezoelectric circular membrane array in a parallel connection for energy harvesting was proposed by Wang et al. and the experimental results showed a significant increase of power output compared to the power generated from a single membrane (Figure 10c). In addition, Rezaeisaray et al. designed an SU-8 membrane-based energy harvester, which used the nonlinear stiffness from stretching the membrane based on Duffing's equations (Figure 10d). In that work, the nonlinear stiffness was fitted through the load-deflection behavior of a membrane obtained by the finite element method, and a frequency bandwidth of...
146 Hz was obtained. The proposed membrane-based energy harvester was suggested to be used to design polymer membrane-based microstructures for small size energy harvesters with low resonant frequencies. Additionally, an example of a bistable membrane-based device was designed by Dogheche et al.\[162\] with a piezoelectric micromachined ultrasonic transducer (pMUT) used as a mechanical to electrical energy scavenger. This pMUT device was subjected to an acceleration between 0.5 and 2 g (mimicking a hand shake) and the experimental results showed that the pMUT can generate power from both linear (elastic) and nonlinear (bistable) mechanical responses.

Recently, membrane geometry-based energy harvesters have become increasingly attractive as a means to leverage the properties of emerging soft materials, which could be utilized to target lower frequency vibration sources. In particular, electroactive polymers with large strain capability are investigated for membrane-based energy harvesters. More recently, two resonant frequency tuning approaches developed by the author via the application of membrane tension. Benefiting from the high electromechanical performance of an electroactive polymer (3M VHB 4910), tuning via applied mechanical stretch and an applied bias voltage for the EAP circular membrane-based energy harvester were investigated as a means to match the resonant frequencies of the harvesting mechanism with the ambient source vibration frequencies.\[160,161,163,164\] In bias voltage tuning approach, the essential tuning mechanism based on the effective stiffness theory is proposed, which describes the effective resonant frequency of the EAP membrane-based energy harvesting system as a result of both mechanical stiffness and electrical stiffness contributions to the overall system effective stiffness as shown in Figure 10e. A summary of reported tunable membrane-based energy harvesters with the proposed/potential tuning approaches is listed in Table 4.

### 3.4. Comparison of Frequency Matching Techniques

As discussed above, in general, there are two approaches (resonance-based tuning and expanded bandwidth) that could be used to implement frequency matching in order to maximize the power output of the energy harvester, with a wider frequency bandwidth desirable for the applications where there is a time-dependent, varying source frequency. The first approach, based on resonance-based tuning, adjusts the resonant frequency of the energy harvester to match the most energy-intensive frequencies of the ambient vibration, and is one possible solution to address frequency matching in order to maximize the power output of the energy harvesting device. There are several methods to implement this resonance-based tuning mechanism, including changing the effective mass and geometries of the structure and altering the effective stiffness. A comparison of methods for broadband being pursued in the area of energy harvesting is listed in Table 5. Generally, the resonant frequency tuning approach is more efficient than the approach of expanding the bandwidth, since such a tuning mechanism is able to harvest more net energy at various frequencies. Among the frequency tuning methods, changing the effective mass or adjusting the geometries of the energy harvester are difficult to be performed during the device operation. Therefore, adding a variable stiffness to the system and hence the ability to change the system effective stiffness is a promising and effective way to implement resonant frequency tuning. However, the induced additional stiffness may require extra systems and energy to realize the tuning method.

### Table 4. Summary of recent reported tunable membrane-based energy harvesters.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo et al.[158]</td>
<td>2014</td>
<td>Pressure</td>
</tr>
<tr>
<td>Palosaari et al.[157]</td>
<td>2014</td>
<td>Multiple structure</td>
</tr>
<tr>
<td>Wang et al.[156]</td>
<td>2011</td>
<td>Nonlinear (stiffness)</td>
</tr>
<tr>
<td>Rezaeisaray et al.[159]</td>
<td>2015</td>
<td>Nonlinear (bistable)</td>
</tr>
<tr>
<td>Dogheche et al.[162]</td>
<td>2005</td>
<td>Bias voltage</td>
</tr>
<tr>
<td>Dong et al.[140]</td>
<td>2016</td>
<td>Mechanical Stretch</td>
</tr>
</tbody>
</table>

### Table 5. Comparison of methods for broadband being pursued in the area of energy harvesting.

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance-based tuning</td>
<td>1. More efficient to harvest more net energy at various frequencies</td>
<td>1. Changing the effective mass or adjusting the geometries of EH are difficult to be performed in practice.</td>
</tr>
<tr>
<td></td>
<td>2. Changing system effective stiffness is an effective way to tune frequencies.</td>
<td>2. The induced additional stiffness may require extra system and energy to realize tuning approaches.</td>
</tr>
<tr>
<td></td>
<td>3. The effective stiffness tuning approach can be adapted for MEMS device.</td>
<td>3. Damping maybe increased in some cases (such as in axial stiffness tuning)</td>
</tr>
<tr>
<td></td>
<td>4. Preferable in piezoelectric and magnetic EH mechanisms.</td>
<td>4. Limited frequency tuning range</td>
</tr>
<tr>
<td>Expanding bandwidth</td>
<td>1. Completely passive approach, no energy required for tuning</td>
<td>1. Limitation of design space for multiple discrete elements</td>
</tr>
<tr>
<td></td>
<td>2. Nonlinear EH improves the performance with a wider bandwidth</td>
<td>2. Power density decreases</td>
</tr>
<tr>
<td></td>
<td>3. Fast response of bistable EH</td>
<td>3. Complex energy storage design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. When one structure is in resonance, while the other (n − 1) structure will not be in resonance, limiting the device performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Complexity in design and implementation regarding the interdependence parameters for practical implementation</td>
</tr>
</tbody>
</table>
addition, approaches developed at small length scales to tune the effective stiffness of NEMS and MEMS devices operating at very high frequencies\textsuperscript{[165–167]} may be adapted for energy harvesting applications targeting appropriate frequencies.

On the other hand, the second approach as summarized in Table 5 is to widen the bandwidth of the energy harvesters themselves in order to implement frequency matching. The attractiveness of this method resides primarily on the fact that it is a completely passive (no energy required for tuning) approach that is relatively straightforward to implement if manufacturing issues can be readily addressed. However, a limitation for the multiple structure method is the number of discrete elements (and hence frequencies) that can be accommodated in the design; in addition, as the frequency bandwidth (and hence the number of cantilever beams) is increased, the power density of the device necessarily decreases. In addition, for the multiple structure energy harvester, while one beam will be in resonance, contributing to the power output at a given frequency, by definition the other \((n-1)\) beams will not be in resonance at a given time, which significantly limits the device performance. With regards to nonlinear energy harvesting approaches, although the performance of the energy harvester can be improved with a wider bandwidth, the practical implementation increases the complexity in design and implementation regarding the interdependence of many parameters.

4. Source Driven VEH

Biology-based energy harvesting offers a lot of opportunities for charging low-power devices. For over 20 years, the human body has been subject to investigations into its potential for energy harvesting in small electronic devices\textsuperscript{[168]} since the device power requirements have decreased substantially and the capabilities of energy harvesters have grown. In the human body alone, there are opportunities for harvesting thermal and biomechanical energy from human motion and periodic expansions and contractions of organs such as the heart and lungs. Biochemical methods for energy conversion, such as biofuel cells, have also been investigated.\textsuperscript{[169–171]} In addition, TENG have offered some interesting advantages in specific impact based motions. They have been developed to solely power wearable electronics by utilizing TENGs placed within shoes\textsuperscript{[172]} and within tube-like structures for multidirectional harvesting that can be integrated into clothing.\textsuperscript{[173]} Along with biomechanical energy sources, biofuel cells\textsuperscript{[169–171]} and thermal gradients\textsuperscript{[174]} on the human body have been investigated for their potential in energy harvesting.

Mechanical energy from different aspects of the body has been shown to have large amounts of available power. For example, the available power from breathing is 1 W, blood pressure is 0.93 W, from upper limb motion is 35 W, and from walking is 67 W.\textsuperscript{[175]} However, these motions are often nonperiodic, can be rotational, occur at very low frequencies, and can occur in multiple directions; making harvesting energy from these motions a challenge. Cadei et al. overviewed many of the available power from different body motions during different activities as well as temperature gradients across the body.\textsuperscript{[176]} On the other hand, one of the more interesting future developments will be in the advent of autonomous cardiac pacemakers. Advancements in microfabrication and bioengineering allowed the implantable pacemakers at a small size with a satisfactory level of reliability. However, periodic surgeries to replace the lithium-based batteries for the pacemakers may cause the safety and comfort issues for the patients, and certainly increase healthcare costs from the economic aspects. Vibration-based energy harvesters can replace the traditional pacemaker lithium-based batteries and will power the pacemakers directly from the varying heartbeat vibrations without an external power source. Therefore, the potential vibration energy harvesting device will provide the patients with safer, more convenient and less maintenance treatments without periodic surgeries, and a low-cost energy solution for the implantable pacemaker applications.

On the other hand, when considering the human body as a source input for energy harvesting, it is often overlooked that the energy harvesting process can influence the source (the human body). Energy harvesting devices can increase the load on the body leading to an increased metabolic cost. For example, muscle movements can be characterized in two ways, as positive and negative work. Positive muscle work is where the muscle generates motion through contraction. This typically comes at an increased metabolic cost. While negative muscle work is where the muscle acts like a brake when muscle contraction is released, working in an opposing direction to the contraction. This typically has a much lower metabolic cost. Riemer and Shapiro\textsuperscript{[176]} discussed the disadvantage of harvesting mechanical energy from positive muscle work and the advantages from harvesting mechanical energy from negative muscle work. Therefore, ideally, energy should be harvested where it would otherwise be lost to the surroundings or have a minimum impact on the source. Since the efficiencies of muscles are much higher for negative work, energy harvesting devices that are positioned to replace the negative muscle work would have less of a metabolic cost. Therefore, optimized locations for mechanical energy harvesting of negative muscle work during various bodily movements should be considered as guidelines for device designs.\textsuperscript{[176]}

The following sections will discuss in more detail examples in which researchers have made use of ultralow frequency in vivo sources, animal/human biomechanical motions, and bioinspired designs for improving energy harvesting outputs.

4.1. Ultralow Frequency In Vivo Sources

Biology tends to operate at low frequencies, the heart expands and contracts at \(\approx 1–2\) Hz, the lungs inhale and exhale at \(\approx 0.2–0.5\) Hz. Typical vibration-based energy harvesting devices, whether they make use of the piezoelectric effect, electrostatic or another mechanism, tend to optimally operate at frequencies greater than 100 Hz and so the main operating frequencies of some of the primary periodic mechanical motions of the human body are difficult to design for. In this section we will discuss vibration-based EH designs that have attempted to harvest energy from periodic organs at these low frequencies.

Among various in vivo energy sources in the body, the motion of the heart is particularly compelling, and is of interest for cardiac energy harvesting and further powering implantable biomedical devices. For example, flexible mechanical
energy harvesters have been developed using PZT-ribbons to harvest energy from numerous organs. These devices were mounted to the right and left ventricles as well as the free wall of bovine and ovine hearts. The devices were also mounted on the lungs and diaphragms of the animals. Each of these locations showed electrical energy harvesting capabilities, with varying levels of electrical output. As expected, the orientation and placement of the device on the various organs affected the level of output, but the study showed that harnessing electrical energy from these organs was feasible.

Others have also investigated energy harvesting of the heart and lungs of animals, Li et al. implanted a nanogenerator into a live rat to harvest energy from the breath and heartbeat. By utilizing ZnO nanowires the periodic expansion and contraction of a rat’s diaphragm during breath provided the displacement to drive the device. The energy gathered was based on the stretching of muscles surrounding these organs. In addition, a theoretical and experimental approach to harvest energy utilizing arterial expansion investigated the potential for blood pressure to act as the driving force behind a unique nanogenerator. Designs were tested using tubes to mimic the human iliac artery with a diameter of 10 mm. They were later prototyped using a pig aorta segment.

Recent examples of implantable energy include an energy harvester based on the beating heart by a mass imbalance oscillation. Implantable energy harvester utilizing the pulsation of ascending aorta, a piezoelectric nanogenerator embedded between the epithelium and muscle in the thigh region harvesting the mechanical energy of the legs. However, almost all reported implantable energy harvesting designs have little to no clinical translation. That is due to the fact that the placements of these energy harvesting devices need suturing directly onto the epicardium or pericardium requiring additional open-chest surgeries for patients. The procedure of suturing such energy harvesting devices directly onto the patients’ heart, especially pediatric patients, inevitably introduces potential risks to the patient. An energy harvesting device that requires a thoracotomy is not an approach that will be accepted clinically. There is a lack of promising technologies that can efficiently covert the mechanical energy of the heart into electrical power without a thoracotomy and interfering with the cardiovascular functions. More recently, low profile, modular and compliant thin film energy harvesters were developed based on existing cardiac pacemaker leads, with minimal risk of interfering with the cardiovascular function. The porous piezoelectric cantilever converted the kinetic energy of a pacemaker lead motion into an electrical power output, or a buckled beam array design was employed to utilize the bending of the lead of a cardiac pacemaker for generating electrical energy.

### 4.2. Animal/Human Biomechanical Motions

Harvesting energy from biomechanical motions in the human body could directly power various wearable and implantable devices. In Figure 11 we see a schematic representing many of these EH devices making use of various mechanical energy sources in the human body. The human’s walking gait has been shown to produce a large enough force that multiple types of energy harvesters have been developed to translate its motions to useable energy. The heel strike has been studied for many years with Paradiso and Starner being early researchers. Later, they developed a flexible piezoelectric foil stave to harness sole-bending energy and a reinforced PZT dimorph to capture heel-strike energy. By using a motor as a generator, Rome et al. developed a suspended-load backpack EH system, which can generate power up to 7.4 W during the human’s normal walking. The energy generated by this device was much higher than the piezoelectric shoe generator. A variety of vibrations due to impacts such as heel strikes are produced by biomechanical motions of human and animal arm and leg motions. There are also several off-the-shelf harvesters that have been shown to be capable of harvesting walking energy. In addition, because much of the vibrational motion is nonlinear, care must be taken to effectively design and simulate these devices to take advantage of the motion. Among different body motions, the knee is a common area for investigation of energy harvesters. Pozzi and Zhu developed a model for a plucked PZT piezoelectric bimorphs for knee-joint energy harvesting utilizing a frequency upconversion strategy. Deflection of numerous piezoelectric bimorphs via a plectra within a ring mount served as the strategy for coupling high frequency resonance cantilevers with low resonance vibration from walking. The device was worn on the external side of the knee and fixed by braces. Donelan et al. design a knee-based device to harvest walking energy during the negative portion of the energy cycle. They explore how energy harvesting can actually be used to improve body efficiency while obtaining energy for wearable devices. In addition, Almouahed et al. embedded four piezoelectric elements within the surrounding area of the knee for applications with a new generation of instrumented knee implants for total knee replacements. The piezoelectric elements were developed to act both as instability sensors and as their own power supply. These devices were expected to help with assessing the imbalance of different ligaments within the knee, and when surgical intervention might be necessary. Other placements on the leg have been investigated for their energy harvesting capabilities. For example, Wei et al. attached a PZT bimorph cantilever to the leg of a person walking on a treadmill at different speeds. The device made use of a frequency upconversion strategy which converted low frequencies from leg movements into high-frequency vibrations closer to the resonance of the PZT bimorph. Other strategies have made use of the hip. Detecting the loosening of a hip prosthesis is difficult with imaging techniques. For this reason, Morais et al. developed a sensor for detecting hip loosening while also powering the sensor with an electromagnetic based energy harvester. More recently, Smilek and Hadas developed an energy harvester for a cochlear implant that will require 150 µW of power. They measured vibration patterns of humans walking at different speeds from a mount on the head. The study showed dominant frequencies in a range from 1.69–2.44 Hz depending on the walking speed and style of person walking. Higher frequencies up to 30 Hz were also present but in smaller magnitudes, offering a range of frequencies to optimize devices for powering cochlear implants.

Motions from other moving body parts have also been investigated for their energy harvesting capabilities. Cantilever devices
have been mounted on the wrist and head, and nanowire based nanogenerators have been placed on fingers. ZnO nanowire nanogenerators were also placed inside live hamsters to test their energy harvesting capabilities within live animals where motions become more complicated. Studies have investigated the feasibility of implanting energy harvesting devices to power lower power electronics. Specifically, one group used a piezoelectric nanogenerator embedded between the epithelial and muscle layer in the thigh region harvesting the mechanical energy of the legs. A summary of recent reported biomechanical energy harvesters is provided in Table 6.

4.3. Bioinspired EH

Engineers are always inspired by nature. While the coupling of mechanical to electrical energy for storage is uncommon in biology, other natural structures offer great potentials for improving energy harvesting system. More recently, researchers have taken inspiration from electric eels, electric fish, sharks, sponges and biological cells. With a focus on vibration-based energy harvesting, Joo-Hyung Kim et al. studied the Gnathonemus petersii (electric fish) which has a trunk-shaped fin that aids in the storage of electricity in its electric organ. By mimicking the shape of these fins, they were able to show a 45% power output improvement when compared to a conventional cantilever configuration for harvesting vibrational mechanical energy. As the interests in mechanical energy harvesting are growing, more device designs will be inspired by the natural sources for flexibility and seamless interfacing with the human body.

5. Conclusions and Perspectives

5.1. Conclusions

There are a large number of significant environmental vibration sources which could be used as the basis for energy harvesting. It is in general necessary to match the resonant
frequencies of the energy harvesting device with the possible target ambient vibration frequencies to maximize the level of energy harvested. Vibration energy harvesting approaches can be modeled as a single degree of freedom, second-order spring–mass–damper system with the energy harvested by the transduction method modeled as an added electrical damper in addition to the mechanical damping present in the system. The four most common energy harvesting mechanisms are reviewed and compared based on the principles for recent progress of piezoelectric, electromagnetic, electrostatic and triboelectric EH devices.

In this work we also discussed and reviewed resonance-based tuning and expanding bandwidth approaches for VEH for a wide bandwidth of environmental source frequencies over which appreciable power can be harvested. Experimental data presented in the literature for two commonly used mechanical structures, a cantilever beam and membrane-based geometry, are discussed. For the cantilever-based energy harvesters, the tuning approaches can generally be classified as targeting one of three approaches: 1) changing the effective mass, 2) altering the effective stiffness, and 3) expanding the bandwidth. In addition, the tuning mechanism and potential tuning approaches for the membrane-based energy harvester are further discussed and summarized in this work.

In addition, source drive VEH and sensing devices are reviewed in this work, specifically from ultralow frequency in vivo sources and animal/human biomechanical motions, to bioinspired designs for improving energy harvesting outputs. The human body provides numerous sources of untapped energy which all show some promise in their capabilities for harvesting energy to power low power electronics. Both wearable and implanted harvesters are currently being studied. The longevity for many long-term implantable devices will be determined by the battery lifespan, and thus energy harvesting provides a unique way of extending these lifespans. Many challenges exist in utilizing biomechanical energy to power these electronics. For example, in live bodies the direction of applied forces is not often linear and occurs at very low frequencies. Methods for coupling these forces need continued development to create optimal operating conditions. In addition, size constraints are also an issue, where implanted harvesters must have limited volumes because it is placed in the human body, typically this is less than 1 cm³. Long term biocompatibility and general wear and tear of these devices has not been thoroughly tested and as the field moves closer to fully autonomous implantable devices these studies will become vital in influencing improved designs.

Vibration-based energy harvesting has attracted wide attention due to its great potential as a high power density and long lifetime energy source. However, there are still certain challenges to address in order to optimize the performance of a vibration-based energy harvesting system. In this section, some of the important challenges and perspectives are presented, including the opportunity for integrating new high performance materials for optimal energy harvesting system performance, research efforts toward an autonomous self-tuning energy harvester system, and future development of VEH in healthcare applications.

5.2. Multifunctional Smart Materials

From the materials perspective, energy harvesting is motivating the discovery of improved or new materials with novel properties for efficient and high performance of energy conversion, which is important challenge for energy harvesting. In general, appropriate materials need to be carefully selected for the particular application. Among various materials, piezoelectric materials (including single crystals, ceramics, and polymers) are the most commonly used materials for the vibration-based energy harvesting due to the high efficiency and power output factoring in size and cost. Three of the most common piezoelectric materials pursued for energy harvesting applications are lead zirconate titanate (PZT), lead zinc niobate-lead titanate (PZN-PT), and polyvinylidene fluoride (PVDF). PZT, a polycrystalline ceramic, is the most widely used because of its excellent piezoelectric properties. However, these piezoelectric ceramic materials are very brittle and have generally poor performance in tension. PZN-PT is a single crystal piezoelectric material. While PZN-PT has excellent properties, it is very expensive because there are difficulties for producing very large sizes of crystals. For biomedical applications, PZT and PZN-PT may not be favorable due the heavy metal element of lead, which has negative influence on the human health. However, PVDF, a piezoelectric polymer, has a higher tensile strength and
lower stiffness compared to PZT and PZN-PT, making PVDF attractive in some applications such as implantable energy harvesting devices,[17,201–203] and wearable sensors.[204,205] Recently, the piezoelectric output has been enhanced by three folds through the optimization of PVDF porous structure and electromechanical coupling efficiency compared to solid PVDF thin film.[206,207] It is confirmed that the elastic modulus of PVDF is tunable by changing the size of internal pores.[201] Due to the nature of polymer, PVDF and its copolymers can be fabricated into core–shell fibers,[208,209] which also proves extraordinary toughness, high piezoelectricity, and sensitivity. Later a kirigami PVDF film was proposed to exhibit an extended strain range while still maintaining significant voltage generation compared to films without cuts.[210] In addition, piezoelectric nanowires and nanofibers based on the materials of PZT,[211] ZnO,[68] CdS,[212] BaTiO3,[213] GaN,[214] and PVDF[215] are being developed and are of interest due to their novel properties, with possible utility in nanoscale bio applications.

In recent years, in addition to these widely used piezoelectric materials for VEH, electroactive polymers have also been explored for potential mechanical energy harvesting applications. Among electroactive polymers, dielectric elastomers have drawn great attention due to their excellent overall performance.[216] Therefore, besides simply using energy harvesting materials, which can convert the energy based on the natural properties of the materials themselves, integrating high performance smart materials into energy harvesting structures could also provide a solution for the challenges required to improve the energy harvesting device performance.

5.3. VEH in Healthcare Applications

The human body has a wealth of vibrational energy available for harvesting, but most of it is in the form of low frequency vibrations, such as the beating of the heart, the cycle of air exchange in the lungs, or the human gait while walking or running. All of these vibrational sources have similar issues, including a widely varying frequency and amplitude depending on the body’s activity level. In addition, low-frequency vibrations are often more difficult to capture, as energy harvesters must be geometrically large in order for their resonance frequency to match the target vibration. This all leads to many design constraints for vibrational energy harvesting when the human body acts as a source. However, advances in material science, power management, and device fabrication techniques will continue to open opportunities for harvesting energy from vibrational motion to directly power healthcare-focused devices.

Within the body, implantable devices such as pacemakers can benefit from energy harvesting. Currently, pacemakers will function for much longer than their battery lifetime, which necessitates several battery replacement surgeries over the lifetime of the device. If the pacemaker is able to harvest the energy of the heartbeat, the amount of extra surgeries could be greatly reduced. Several energy harvesters have been proposed as candidates to harvest vibrational energy from the human body in the literature.[167,177,182–183,217,218] However, no practical/commercial EH devices have yet been used in clinical applications for patients. Future directions for implantable EH to be entirely translatable to the clinic consist of improvement of devices performance (especially the current output from piezoelectric-based EH devices), and long-term animal studies, to evaluate devices’ stability and energy storage. Other applications for energy harvesting in implantable devices have also been pursued, including for cochlear implants.[190]

Various wearables, such as fitness trackers, heart rate monitors, and blood oxygenation sensors, already have very low power consumption—most needing to be recharged approximately once per week. Integrating energy harvesters which can draw energy from walking or running would allow these wearables to run indefinitely, greatly increasing their usefulness. Within healthcare, these wearables can offer physicians a look into patient’s health outside of the hospital setting. Energy harvesting developments will give these devices reliability for physicians and reduce issues associated with battery replacement and charging for the patients. Durability and stability of the devices for either energy harvesting or sensing would be critical for practical applications, especially for TENG devices due to the limitation of the effective contact time.

The Internet of Things (IoT) within healthcare has recently become a source of a lot of research interest.[219] In the healthcare setting, IoT gives physicians an easier way to interface with interconnected medical resources to better serve patients. Combining implantable and wearable devices, along with environmental sensors, much of the hardware associated with the body sensor networks (BSN) being developed for IoT applications use batteries for power. This power consumption is a big challenge in bringing IoT for healthcare to a ubiquitous level and is where energy harvesting can have an impact.[219] Beyond the previously discussed implantable and wearable device, environmental sensors have great importance in healthcare IoT for monitoring living environment of patients. For example, RFID tags have been used in these situations.[220] Coupling energy harvesters with these types of passive tags could lead to more on-device data processing and improved communication with the sensor network. This could allow for more autonomous sensors without worrying about the periodic replacement countless batteries. More mobile applications such as in emergency medical services, where the removal of sensors from tethers is very important could also see huge benefits from vibrational energy harvesting.[220]

Improvements in vibrational energy harvesting will lead to not only more than just longer battery lives of current implantable and wearable medical devices but also the development of new autonomous sensors, which previously would not be feasible. What vibrational energy harvesting promises is a more compact, self-sufficient energy source. Coupling these with sensors, utilizing passive transducers such as piezoelectric or triboelectric materials, will lead to a new paradigm for healthcare-focused sensors. The energy harvesting units could be used to power communication and data processing circuitry on the device, leading to fully autonomous sensing platforms for improved patient monitoring.

5.4. Self-Powered Autonomous System

Another future opportunity for the energy harvesting system is to ultimately implement a self-powered autonomous system
that can be used for energy harvesting applications (for example, wireless sensor networks), which is totally independent from the energy point of view. An autonomous energy harvesting system consists of three modules: energy generation, energy conversion and optimization, and energy consumption. From a system-level perspective, one must obviously account for any energy consumption when evaluating the efficiency and performance of an autonomous energy harvesting system.

To address this challenge, several reported energy harvesters have been proposed in the literature. For example, Challa et al.[221] developed an autonomous self-tuning vibration-based energy harvesting device utilizing magnetic stiffness. The developed device consumed maximum energies of 3.3 and 3.9 J to tune to the frequency range from 13 Hz (at 3.3 J) to 22 Hz (at 3.9 J); in comparison the untuned resonant frequency of the device is 18 Hz. Ayala et al.[222] implemented a self-powered control system that autonomously tuned the resonant frequency from 64 to 78 Hz for an electromagnetic vibration-based energy harvester. The tuning mechanism was based on changing the spring stiffness via the application of the axial tensile force between two permanent magnets. In that work, a closed loop control measured the ambient frequency using the phase difference between the harvester output voltage and an accelerometer, with a maximum energy consumption of 202 mJ determined. In addition, Eichhorn et al.[223] designed a tunable piezoelectric energy harvester based on a triple layer piezoceramic plate equipped with two lateral arms, which are used to apply an axial preload. To decrease the average power consumption of the control unit, the idea of a power-saving sleeping mode for the microcontroller was applied and the results showed that a resonance frequency range between 150 and 188 Hz was obtained with consumed tuning energies in the range of 200 µJ.

To implement a practical and completely autonomous energy harvesting system remains a great challenge ongoing work; a comprehensive system level design must consider the different process stages of energy generation, conversion, and consumption. Therefore, there is still ample room to increase the efficiency of energy generation and conversion while continuing to decrease energy consumption. It is promising the new development will ultimately lead to an autonomous and tunable vibration-based energy harvesting system for a broad range of applications, especially for electronics, wearable and implantable medical devices.

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Conflict of Interest

The authors declare no conflict of interest.

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