A review of walking energy harvesting using piezoelectric materials

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Abstract. Harvesting kinetic energies is a sustainable method for generating electricity without depleting natural resources. The main mechanisms for kinetic energy harvesting are piezoelectric, electromagnetic, electrostatic or by using magnetostrictive materials. This study focuses on harvesting of walking energy and aims to compare different technologies used for converting of walking energy to electricity, and identify the most effective technology. Several types of harvester located on body of user to harvest kinetic energy of body during walking, while some pavement slabs are produced for harvesting energy. The paper concludes that the pavement equipped with the harvesters would be more reliable than the body located technologies since it is independent of the physiological parameters. Moreover, the piezoelectric transduction is more desirable due to its advantages such as simplicity and flexibility, while produce less current output than the electromagnetic transduction.

Keywords: kinetic energy harvesting, walking energy conversion, footsteps, piezoelectric generator, pavement

1. Introduction
Energy harvesting or scavenging is the process of capturing the wasted energy from naturally occurring energy sources, accumulating and storing it for later use [1]. In another definition by Kazmierski and Beeby [2] energy harvesting is the conversion of ambient energy, exist in the environment into electrical energy. Harvesting energy is one of the most promising techniques in response to the global energy problem without depleting natural resources. Energy harvesting typically refers to micro- to milli-watts small power generation systems that is developed as a method for replacing or augmenting batteries. It exploits kinetic, thermal, solar sources or electromagnetic radiation sources. The kinetic energy harvesting that is the purpose of this study, converts movement, mainly in form of vibrations, into electrical energy. An energy harvester has typically three main components; the micro-generator for converting ambient energy into electrical energy, the voltage booster to pumps up and regulate the generator voltage and the storage element [3]. Since vibration power generators are mainly resonant systems, the maximum power is generated when the resonant frequency of the generators matches ambient vibration frequency [4]. Regarding the scope of the study that is harvesting kinetic energy of
walking, the frequency of the human movements is less than 10 Hz [5]. Harvesting kinetic energy of the human body including walking energy is one of the methods of providing electricity for low-powered devices through implementing energy harvesting technologies, which in the individual has the potential to become a power generator [6].

2. **Principles of kinetic energy harvesting**
   There are different types of vibration energy to harvest, that have been studied by several scholars, such as human motion [7], ocean wave [8] or harvesting strain from beam elements in critical structures [9]. Energy harvesting from mechanical loading generated in the ground in the shape of compressive forces while people move across the floor, is a sustainable method to generate electrical energy [10]. The generic model of kinetic energy harvesters was first developed by Williams and Yatus [4, 11]. Kinetic energy harvesters, also known as vibration power generators, extract electrical power by employing one or a combination of different mechanisms including piezoelectric, electromagnetic, electrostatic or by using magnetostrictive materials [4]. Many scholars have studied the properties of theses transductions, the advantages and the disadvantages of each mechanism [1]. This study aims to focus on the harvesting of walking energy as a type of kinetic energy. Hence, firstly it is needed to study harvesting the kinetic energy of body during walking and then focuses on harvesting of the walking energy using piezoelectric harvesters in the floor.

3. **Harvesting kinetic energy of body during walking**
   Study of energy harvesting has recently gained attention in order to power portable electronic devices [12, 13]. Human activities as energy sources [14] are considered for harvesting by employing electromagnetic, piezoelectric, or electrostatic transduction methods [12, 15, 16]. In order to maximize power output, the resonant frequency of a harvester (fr), should match the dominant frequency of motion (fm) [7]. Generally, motion energy availability increases as fm increases [17]. The idea of harvesting energy from human motion is based on the fact that the amount of energy used by the body per day, is 1.07×107 J [18], an amount equivalent to around 800 AA (2500 mAh) batteries [19].

   Walking is the main motion in normal human lives, hence, is considerable vibration energy for harvesting [7]. Walking is an economical energy harvesting approaches [14]. [Romero, Galchev [20]] estimated that 1 mW/cm3 power could be produced from human walking that this level of power would energize low-power applications [15]. Therefore, several harvesters are under development and different ways of harvesting motion energy, including inertial energy harvesters, integrating a piezoelectric system, the technology of electrostatic generators based on electroactive polymers (EAPs), or electromagnetic energy harvester. Inertial forces have been used for energy generation either inside shoes [21], within the shoe sole [6, 22], [23] that harvest energy from footfalls or mobile phone chargers integrated in backpacks[24] or phones [25]. Gorlatova, Sarik [7] focus on inertial energy harvesters and studied human physical parameters when harvesting walking energy. They showed that the taller half of the participants, harvested more power than the shorter half (around 20%). Moreover, the average power for going downstairs is significantly higher than for going upstairs. As the measurements of the Gorlatova, Sarik [7] study demonstrate, for prolonged activities, average absolute deviation of the acceleration, frequency of motion, and the average power vary considerably over time due to the physiological parameters changes [7].

   The heel-strike generators using piezoelectric and electrostatic devices [26] with few mW power outputs has gained attention due to the rather high impact forces generated during walking. The main advantage of piezoelectric materials that are mainly used for heel strike devices, is their simplicity for incorporating into a shoe. However, the piezoelectric elements as energy harvesters are proper for low frequencies conditions and the power output of this technology is not enough to power high-consumption devices [27] and limited to nearly 100 mW due to the small displacement and the high generated voltage [28]. The technology of EAPs (electrostatic generators based on electroactive polymers) as the best choice for heel-strike devices have a high power-to-weight ratio [19]. Furthermore, some researches show that use of electromagnetic can generate energy with higher power output [12, 13]. Romero,
Warrington [15] suggested considering careful design for a body located harvester used the available energy of the body to power an electronic device. To increase the power output at low vibration frequency, Zhang, Wang [29] developed the energy harvesters to convert low-frequency vibrations to a higher frequency by employing the frequency up-conversion technique [30, 31]. Their simulations of power generation through magnet and coil arrays show that the high energy-conversion efficiency can be maintained at low vibration frequency and large vibration amplitude [29]. As a consequence, according to Riemer and Shapiro [19] the most power output refers to the technology of EAPs for heel-strike devices. Table-1 shows the output power of different technologies located on the body.  

Table 1. Comparison of different technologies located on the body for converting energy of body motion during walking to electrical energy.  

| Ref. | Type of Technology                                                                 | Output Power          |
|------|-----------------------------------------------------------------------------------|-----------------------|
|      | **Inertial energy harvesters:**                                                   |                       |
| [23] | Body’s own inertia (compression of the shoe sole)                                  | 0.8 W                 |
| [32, 33]| Inertial energy harvesters for a small wireless device, from walking               | 100–200 µW            |
| [7]  | Inertial energy harvesters fits for Internet of Things applications:               |                       |
|      | for trouser pocket placement                                                      | 202 µW                |
|      | for waist belt placement                                                          | 180 µW                |
|      | for shirt pocket sensing unit placement                                           | 155 µW                |
| [24] | Inertial forces inside backpacks                                                  | Few milliwatts to a   |
| [21] | Inertial forces inside backpacks Shoes                                             | few watts              |
|      | **Piezoelectric elements:**                                                       |                       |
| [34] | Piezoelectric generator harvesting the energy of footfall during walking          | 150-675 mW            |
| [28] | The piezoelectric elements for low frequencies conditions and low-consumption devices | Nearly 100 mW        |
| [35, 36]| A cymbal-shaped piezoelectric                                                    | 53 mW                 |
| [37] | Two back-to-back unimorphs                                                        | 8.4 mW                |
| [22] | Harness the heel strike using a unimorph strip                                     | 1.8 mW                |
| [37] | The PVDF stack                                                                    | 1.3 mW                |
| [22] | A stack of Polyvinylidenefluoride (PVDF) sheets shaped                             | 1.1 mW                |
| [38] | A piezoelectric vibration generator                                               | 375 µW                |
|      | **The technology of EAPs:**                                                       |                       |
| [19] | The technology of EAPs for heel-strike devices                                     | 0.8 W                 |
|      | From the heel strike (for a walking person weighing 80 kg at around 4 km/h)       | 2 W                   |
|      | The knees and the ankles (for a person weighing 80 kg)                             | 34 W and 20 W,        |
|      | respectively                                                                       |                      |
|      | **Electromagnetic energy harvester:**                                             |                       |
| [24] | Spring-loaded energy harvesting backpack with a magnetic generator                 | 7 W power             |
| [14, 24]| The biomechanical energy harvester consists of an aluminum chassis and a generator located on a customized knee brace | (4.8±0.8) W          |
| [29] | A hand-held electromagnetic energy harvester from body motion located in a backpack of a user at 3.58 m/s walking speed | 32 mW                |
| [15] | Electromagnetic induction generator located alongside of the ankle for implantable devices | 3.9 µW              |
4. Harvesting kinetic energy of walking using piezoelectric harvesters in the floor

The main technologies used for harvesting kinetic energy of walking through the floor are based on piezoelectric and electrical induction generators, and electrostatic generators based on electroactive polymers (EAPs) [19]. Generally, there are different methods for producing electrical energy from moving people through the pavement based power generation technologies. An unusual approach is the use of pressure changes in the ground when people walk, that is exposed to permanently fluctuating pressure amplitudes. For example, the movement of a dance floor can be used to generate electricity through employing an electromagnetic generator. However, in order to generate a considerable electric power, there is a need to a relatively large deflection of the floor, up to 10 mm. Moreover, it needs a complicated structure that impose high assembling costs. Another example is piezoelectric harvesters in the floor of a subway ticket machine. The harvesters consist of piezoceramic and there is no need to complicated mechanical structures [10]. The rubber mats containing piezoelectric sensors were integrated along ticket gates for Tokyo subways in 2008 [6]. Since in this method, the energy conversion is based on the piezoelectric effect, there is no need for deflection of the ground. The efficiency of this energy conversion depends to the thickness and properties of the piezoelectric material, and the force affecting the piezoelectric material. Higher thicknesses and higher forces generate higher amount of surface charges. Among the different piezoelectric materials, only Polyvinylidene fluoride (PVDF) offers a long lasting functionality under these conditions at a comparable low price. PVDF is incombustible, chemically resistant and can be processed by injection molding. It is less expensive compared to lead zirconate titanate (PZT), and is unbreakable under harsh conditions. Nevertheless, the pure piezoelectric coefficients, the relatively low Curie-Temperature (105°C) and the necessity to stretch and to polarize the material are disadvantages of PVDF [10].

Bischur and Schwesinger [10] studied piezoelectric PVDF-foils for converting dynamic compressible mechanical loads into electrical energy. They found that the higher remnant polarization causes the better the energy conversion. Moreover, electricity generated rises with an increasing number of windings. They concluded that piezoelectric PVDF-foils appear to be very promising compared to PZT ceramic. PVDF as a polymer material is flexible and resistant in mechanical destruction forces. While, PZT as an inorganic ceramic is brittle and needs protection in a harsh environment [10]. Another example of walking energy harvesting through the floor is implementation of both technologies of piezoelectric and electromagnetic along pedestrians footpaths for Crowd Farm project by MIT in 2007 [6].

Wu, Tsung-Tsi, et al. Wu, Wang [39] studied a harvesting floor designed with piezoelectric material, which can convert extra energy of walking motion into electrical energy. Under low frequency condition, the energy generation from piezoelectric material has a low efficiency that is insufficient to drive a wireless module. In order to elevate the energy power of piezoelectric, they adopted the plucked method in their research, which the generated energy is approximately 10 times more than the energy of the forced method. This method changes the frequency from lower one like footstep to higher one like resonant frequency of the beam. Due to the small size of the piezoelectric material, and high power density, the size of the harvesting floor can be minimized [39]. In addition, [Kumar and Chaturvedi [40]] simulated and experimented a model of energy harvester floor tile and concluded that output voltage would be increased by employing high coupling coefficient piezoelectric material, increasing the number of piezoelectric diaphragm per unit area and parallel arrangement of them.

Furthermore, there are some achievements and studies on harvesting footstep through implementing different technologies in order to generate power for lighting LED lamps. One of the products that harvest kinetic energy of people stepping on them and immediately convey tiny bursts of electricity to nearby appliances, is the recycled rubber "Pavegen" paving slabs [41]. The Pavegen tile is a promising method of harvesting footsteps energy and is designed to compress five millimetres when someone steps on them. Since Pavegen has not share the precise mechanism of converting harvested kinetic energy into electricity, some guess that it utilizes piezoelectric sensors [42], while others believe using of electromagnetic technology. The efficiency of tiles in power generation is rather high, which each tile
harvests 6 to 8 joules of energy per footstep. Each step produces only enough electricity to keep an LED-powered street lamp lit for 30 seconds. The system uses 5 % of the power to light the central lamp and the other 95 % of the power either can be stored in internal or external batteries for up to three days or used directly for external applications. Hence, when no central light is required, the output is 100 % of the power [6]. In their first commercial application, they expected that by scattering 20 tiles along the central crossing between London’s Olympic stadium and Westfield Stratford City mall, and estimating 30 million customers, can power half of outdoor lighting at vast London shopping mall. Kemball-Cook, the founder and CEO of Pavegen, mentioned another example of using this slab recently in a big outdoor festival received over 250,000 footsteps that was enough to charge 10,000 mobile phones. He added that it is also easy to install the Pavegen slab as a retrofit on existing pavements, can match their exact dimensions and be replaced one slab with another. He also foresees Pavegen systems to power off-grid appliances such as public lighting, illuminated street maps and advertising, and can be used in dense human traffics areas [41]. The main issue of green slabs of Pavegen is its price. However, the company hopes to see the price drop to below $100 per tile in the near future.

Additionally, Vanz and Karakiewicz [6] proposed a power generating device for safety lighting along the specific stairways in Melbourne, and focused on ergonomics, comfort and safety of the pedestrian as well. They considered four conditions including force of footstep, technology, service provided, and context in their study. They measured the selected ten piezoelectric sensors, generating 300 μJ per actuation (EG300), per tread and two steps, and placed 20 LEDs along two steps. Since per sensor can light the 20 LEDs, hence, they would be powered for 1.5 hour per day. By increasing the number of sensors per tread up to 15 and distribution of 20 LEDs along three stair treads, which is sufficient for safety purpose the duration of the lighting increases to over 3.5 hours. It can be estimated that by considering 10 sensors (EG300) along one stair tread, the power generating system can keep 200 LED light for 10 hours at night time for a higher pedestrian’s traffic pathway, such as the subway in Tokyo, with around 4 million pedestrians daily. By comparing the developed device based on the piezoelectric sensors with Pavegen technology, it could be concluded that the proposed prototype is more efficient, due to the physical occupied space by the systems, and the system efficiency in capturing the footstep energy using the flexibility of the prototype design [6].

As a consequence, both piezoelectric harvesters located on the body and in the floor, can generate power from a microwatt to few watts. However, harvesters located on the body are dependent on the location of the generator and average of the acceleration, frequency of motion, and the power vary, significantly. Therefore, to gain a consistent output, implementing the harvester within the pavement slab is a better choice.

5. Conclusion
The study has reviewed the different methods of harvesting footsteps, the power output and in some cases the applications. By comparing the harvesting energy technologies located on the body and pavement, it is revealed that for body located harvester the power output depends on the physiological parameters. Therefore, it is better to implement the harvester within the pavement slab to gain a consistent output. Furthermore, in comparison between the different types of transductions used in the equipped pavements, although, the output current of the electromagnetic mechanism is high, the piezoelectric technology with the simple structure, flexibility of the design and geometry, small size of the sensors, the ability of easily meshing into hybrid materials has made the piezoelectric transduction desirable. Moreover, four proposed interrelated conditions, play a main role in achieving the desirable results. It is obvious that the number of pedestrian is the main factor when selecting the type of technology and can be effective on the generated power output. In the other word, the type of transduction has to be selected according to the number of footsteps and the needed services. The study recommends more exploration on the piezoelectric properties to optimize the power output in order to use the technology for the pavement in different application.
6. References

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