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Energy Harvesting from Close Type Footwear: A Smart Design Approach

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Article

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ABSTRACT

The mechanical energy harvesting from human body, particularly from the feet, is an alternative process for acquiring potential electricity. Human body weight-pressure produces mechanical energy during walking and running. In this study, a special type of footwear was designed by inserting piezoelectric transducer (PZT) under the heel area to convert the mechanical energy into electrical energy. The experiment has been conducted with a circuit comprising of bridge rectifier, capacitor, and a DC-DC converter with an external output connection. It has been found that the AC voltage maximum is 43 V. When the AC voltage was converted to continuous DC, it was found the voltage decreased drastically. The highest generated energy has been found to be 317.52 mJ for two hours (8000 steps per day). Our special type of shoe and circuit design have demonstrated the feasibility of harvesting the mechanical energy into the electrical energy from piezoelectric materials.

KEYWORDS

energy harvesting, piezoelectric transducers, smart shoe, electrical energy

INTRODUCTION

The conventional energy sources are declining gradually towards positive entropy due to the rapid growth of population and commercial development [1,2]. Therefore, non-conventional alternative energy sources such as human movement-based activities is crucial that consume efficient renewable energy by improving energy conversion structure to cope up the energy demand [3].

Nowadays, the development of advanced technology has targeted that no energy (even trace amounts) will be remained unused and transferring into another alternative energy [4]. The lost-energy harvesting and reuse are the most suitable alternatives with less consumption in line. Power efficiency development and reduced power consumption requirements have been increased, performing the advancements in microprocessor technology [5].

However, it is an urgent need to meet the demand for electrical energy. Different plans of renewable energy sources are being developed and utilized to meet the energy demand. Energy harvesting from mechanical vibrations, deformations, elastic stresses, sounds, sunlight, and artificial lights with solar panel, natural wind, waves, and tides have already been examined. Moreover, energy from human body activities, like limb movement, breathing, blood pressure, mechanical stresses, walking, jumping and running have been looked at as usable energy sources. Many low power portable electronic devices are being designed and used to harvest the lost energy and utilize it [6]. Among them, energy harvesting from human body is a better alternative due to the easy conversion of potential energy into electric energy. Mechanical energy during walking, running and jumping plays a vital role as an alternating small power energy harvesting [7]. Since so many researchers have demonstrated ideas, technique has gained much popularity to harvest non-conventional energy that stimulated our interest [8].

Piezoelectricity is a more feasible option that is helping to meet the low power electronics devices energy demand [9]. This is a clean and sustainable electric energy harvesting from mechanical movement of human with an attractive measure. Piezoelectric energy harvesting has more advantages as it is environmentally friendly, nonconventional, has no need for an external fuel supply, can easily be maintained, has mature and simple circuit and technology, has no need for manual work, available all year round, has no fuel transportation problem, reliable, economic and so on. The energy storage density of piezoelectric, electrostatic and electromagnetic device motivated energy harvesting by the piezoelectric transducer (PZT). Several types of crystalline ceramic and polymer piezoelectric transducers with different shapes and designs are available for experimental and practical use. PZT and polyvinylidene difluoride (PVDF) transducer have both the better piezoelectric effect. But PZT generates higher voltage energy than PVDF, yet the PZT has no better wear flexibility and durability [10]. One or more layers of PVDF polymer and round or square type PZT disc are available for experiment. Generally, square-type disc does not show better results. Square disc generates maximum 5.7 V but round disc generates 15.3 V during walking for the weight of 73 kg [11]. For all these applications, owing to the large values of stress/strain encountered, flexible piezoelectric materials are the natural choice over the brittle ceramic materials.

The piezoelectric energy harvesting on shoe must have a distinctive feature, like being more convenient, appropriately sized and fitting, comfortable with functionality and no manual battery recharging. Normally, our body weight (50-100 kg) pressure is applied on the bottom surface of the shoe through feet during walking [12]. In different stages, a different weight pressure was measured which determines the suitability of piezoelectric disc positioning to get the maximum power supply. But in practice, piezoelectric disc inserted in the shoe does not get the total body weight pressure altogether [13]. As a result, the piezoelectric shoe should be fabricated to get the highest body weight pressure. This pressure (mechanical energy) imposed on the shoe can be converted as electrical energy through piezoelectricity. Piezoelectric transducers produce electric voltage i.e., immediate current flow from this mechanical pressure energy. The more the pressure on the shoe, the more the energy is produced and harvested. When a person walks or runs, it creates pressure on the shoe i.e., shoe sole, heel and toe area.

Some researchers inserted single or more attached discs, sheets of PVDF in various parts (heel, mid foot, toe - the area with the most contact) of the shoe with different way-springing systems, racks and pinion sections with a gearwheel system [14]. Besides, normal circuit structure was not capable of generating enough power and complex circuit components were required [15]. At first, this circuit system produced more AC voltage for a single footstep. This AC voltage was regulated to DC continuous supply to get an expected power. Researchers showed many types of circuit design and testing the piezoelectric energy harvesting in the shoe and in other different areas. Basic on average, a circuit diagram of the attaching piezo disc on heel, toe or mid foot of the shoe generates discrete AC voltage [16]. The diode (bridge rectifier) rectifies AC voltage to DC voltage, converts pulsating DC to fixed DC with the capacitor or the DC-DC converter. Storing the power in the capacitor or the battery, regulating the generated power with a different circuit system (Darlington pair diagram) was developed to adjust to the charging device and applying the power generated by different external device-mobile charging, emergency lighting, LED lights etc. Darlington pair diagram increases the input voltage and decreases the current value. Normally, a single piezoelectric transducer produces a very small amount of power. Hence, the best performance transducer selection, perfectly positioning the material on the shoe, the most output oriented circuit diagram designed, transporting the total output current to the output storage, are the major concerns to get the expected highest output result [17]. Thus, piezoelectric effect can play an important role as an alternating non-conventional energy source. With the piezoelectric power generated, GPS tracking system can also be embedded utilizing piezoelectric power to run the GPS tracker [18]. From this idea, a piezoelectric floor was proposed to harvest energy freely, on a crowded dance floor, ticket counter, jumping floor etc. [19]. It can also be implemented in ultrasound imaging, sensing pressure, chemical and biological sensing, automotive application, on a railway station floor, a rail line or an airplane runway ground [20]. Piezoelectric sidewalks and walkways at cities and urban areas would help to power community spaces, markets, streetlights, public buildings, educational institutions, playgrounds, and lifting system. Piezo disc could also be integrated with a stationary surface instead of moving objects and it would require less maintenance. In future, frequent study can bring about better energy sources than conventional energy sources. However, the breakage assessment of the piezo and system reliability is equally important for durability. An investigation of the feasibility of placing the piezoelectric disc into the shoe and the breakage of piezo from a long-term perspective will be investigated in the future.

In this research, a special smart-type of a shoe and circuit design was developed by placing piezoelectric discs under the shoe-sole and with the same body weight. The different voltage and its efficiency by generated energy was investigated systematically. The amount of energy was too low to charge an analogue mobile phone battery. But it is our goal to unobtrusively collect energy for LED lighting and analogue mobile charging etc. This problem was approached by using a proper and advanced circuit design and development.

EXPERIMENTAL

Materials and Methods

Piezoelectric elements

Piezoelectric Lead Zirconate Titanate (PZT, Sparkfun, Model no-SEN-00110, USA) ceramic type piezoelectric energy harvester was used to harvest the electrical energy from the mechanical foot pressure applied on the shoe. The piezo material has two positive (inner side area) and negative (outer side area) poles that produce voltage after mechanical deformation. Different components of a circuit, such as piezo-electric transducer, diodes (Schottky), resistor, capacitors, LED lights and a switch, were used for the experiment.

Experimental set-up

Shoe materials (upper leather, soles, insoles and other accessories) were collected from the Institute of Leather Engineering and Technology (ILET) Footwear Lab, University of Dhaka. A hand-made special designed Oxford type working-shoe was used for the testing of energy conversion. It has helped to measure and take the frequent data during the standing and walking conditions. Frequent tests were made in the heel area. Piezoelectric material was attached to the up-insole by using adhesive and covered with extra cushioning and an in-sock. The attached piezoelectric wire was introduced in between the heel-insole edge and the lower heel upper area with piercing into the sole. Finally, piezoelectric wire was taken towards the heel cave. The heel was designed to have enough space to keep the total circuit.

Perfectly positioning the piezo material on the shoe is important in order to get highest power for various applications. The perfect positioning means the highest pressure is on the shoe as output voltage increases proportionally with the pressure applied. During walking or running, foot pressure is applied on different parts of the shoe, like the heel, front toe, tread line, middle area between heels and the tread line area. However, maximum pressure is applied on the heel and toe area. Mechanical energy (vibrational and rotational energy) from foot pressure creates deformation of the piezoelectric transducer embedded into the shoe and is converted to electrical energy (voltage generation). Moreover, the pressure is directly proportional to body weight**.** Experiments were made on the area of the heel where most of the contact happens. Piezoelectric disc was inserted in the heel area and attached with adhesive. The disc was covered by foam sheet as cushioning to lessen the sudden pressure on the disc as it could damage the crystal structure abruptly. Single disc, two discs or three discs in series and a parallel connection were frequently experimented with to get the highest and reasonable value.

Circuit insertion into the shoe

Heel fabrication was done in such way that total circuit components could be easily and safely inserted without short-circuiting, as shown in Figure 1. The wire of the piezoelectric disc was pierced in between the heel area surrounded by the insole edge and the leather upper material. It was carefully designed so that the wire cannot come into contact. A cavity was made in the sole and the upper part of the heel, to take away the wire that comes from the piezoelectric disc to the heel. Then the wire drawn to the sole hole to be joined with other circuit components.

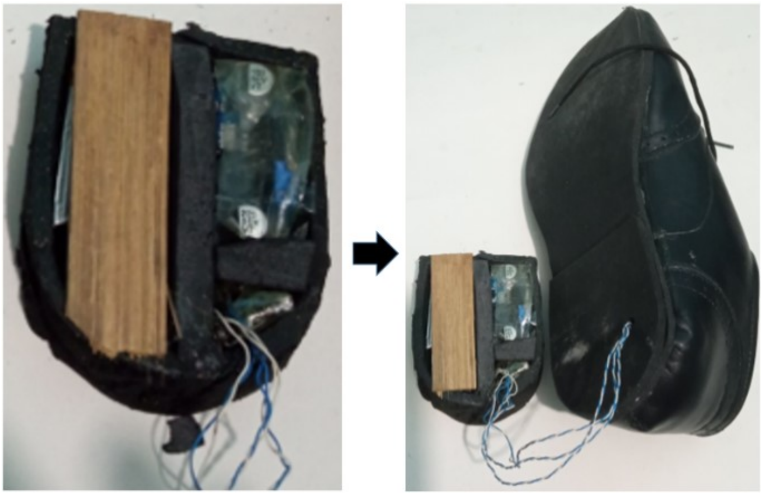

Figure 1. Inserted circuit at the heel portion and complete preparation for sole and heel attachment

Heel fabrication was done in such way that total circuit components could be easily and safely inserted without short-circuiting. The area of the heel was reduced to create sufficient space for the components. Every component was wrapped with non-conductive tape. There was no lack of comfort as the total weight of the inserted components was only 45 g. There was some partition to keep the components separate so that no components could come into contact. A piece of wood was used as a support in order to cover the gap and to increase the strength so that the footfall pressure would not damage the heel structure and disturb the circuit structure. It was made to have room for every component required for the generation of power. Finally, the complete piezoelectric energy harvesting shoe was made for a practical purpose.

Experimental methods

The process of energy harvesting from a basic oxford shoe is summarized in the following (Figure 2). At first, this circuit system produced different and discrete AC voltage for every single footstep pressure. Then diode (bridge rectifier) rectified AC voltage to DC voltage (pulsating). The oscilloscope (GWINSTEK, GDS-1072-U) took the pulsating DC voltage graph. Next, the pulsating DC voltage was filtered to get fixed and direct DC voltage by capacitor or DC-DC converter. After that, the DC voltage was stored in a capacitor or battery and a single LED light was lighted.

Figure 2. Flow chart of piezoelectric energy harvesting

RESULTS AND DISCUSSION

The three piezoelectric discs were attached on the upper part of the insole of that working shoe. Single or a serial connection of discs was not able to generate more current even though it had higher voltage. As a result, the parallel - connected discs were employed to get more current along with the desired voltage. Then, it was connected with a full wave bridge rectifier to rectify the AC voltage to pulsating DC voltage. Four Schottky diodes were used to make the bridge rectifier. After that, it was connected with a capacitor (22 μF and 50 V) and direct DC voltage was generated. Finally, a LED light was connected for observation (Figure 3). Different trials were taken to get the required value. DC-DC buck converter was also used but it did not get the preferable output.

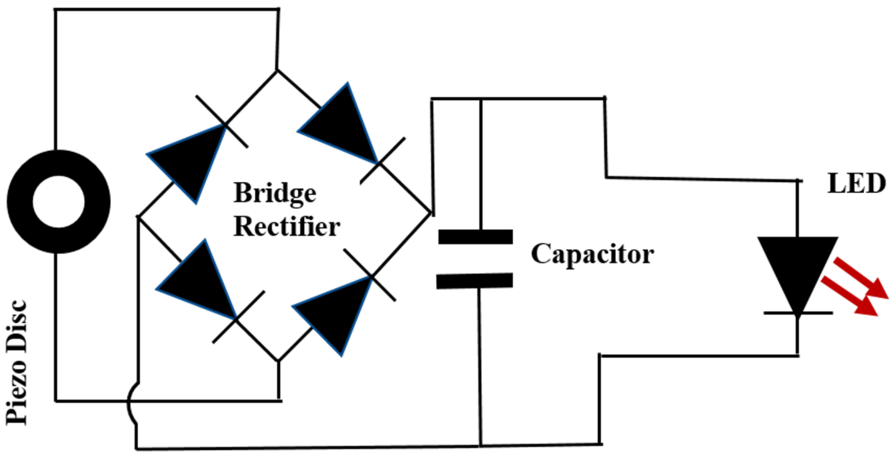

Figure 3. Schematic drawing of piezoelectric energy harvesting

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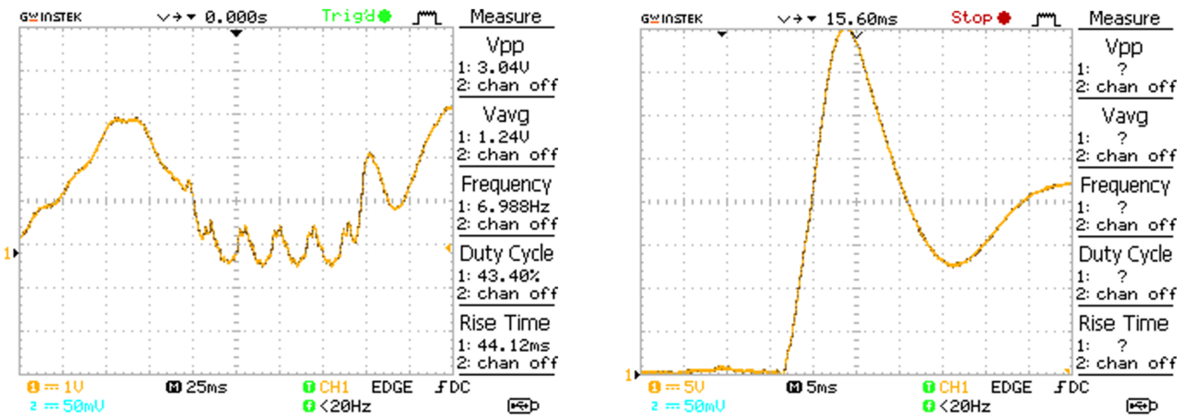
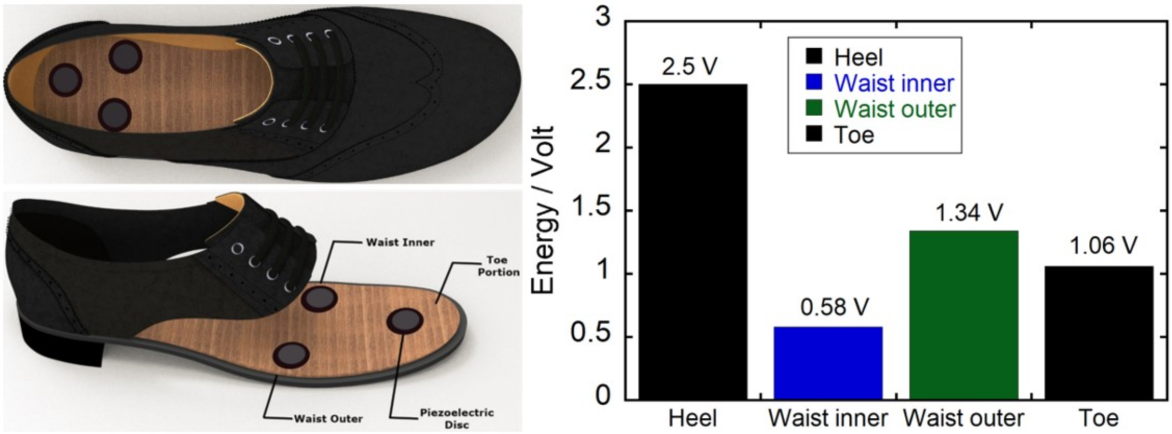
The working circuit for harvesting the electrical energy was firstly designed. Several trials were taken to get the highest output result. The amount of AC voltage was high enough to get the expected energy. It could not be found more due to high resistance. It was found that when the LED light was connected to the output capacitor, the voltage lowered to about 2 V and the LED light was glowing. The connection of the piezoelectric disc with the bridge rectifier showed the pulsating DC voltage. Two graphs were made showing different waveforms over different weight and footsteps. Every graph was different from each other showing voltage of peak and average value, frequency and time with the rise of values and the duty cycle. Here, random mechanical energy (from pressure) showed different voltage values. The following two graphs showed pulsating DC voltage waveforms (Figure 4).



a) b)

Figure 4. Waveform shape for pulsating (a) DC 3.04 V; (b) DC 23.2 V

Figure 5(a) shows the positioning of the PZT disc in different parts of the shoe and Figure 5(b) shows the maximum voltage during walking. It is clear that the highest amount of voltage was generated at the heel, which was 2.5 V. The lowest amount of voltage was generated at the inner waist portion (0.58 V) due to the lack of pressure on the insole during standing as well as walking. No pressure is imposed onto the piezoelectric material in the inner waist portion. After the inner waist portion, the power generation starts to increase to toe portion. During walking, the heel receives the body pressure first then the pressure distributes to the midfoot and forefoot.



a) b)

Figure 5. (a) Positioning of piezo disc in different position (b) Generated energy (Volt) at different portion

Pressure value on the whole shoe was taken for both legs (left and right) by Dynamic Pedograph (Model No: PED-01, BiBEAT Ltd) shows in Figure 6. It is clearly seen that the maximum pressure is induced in the heel area.

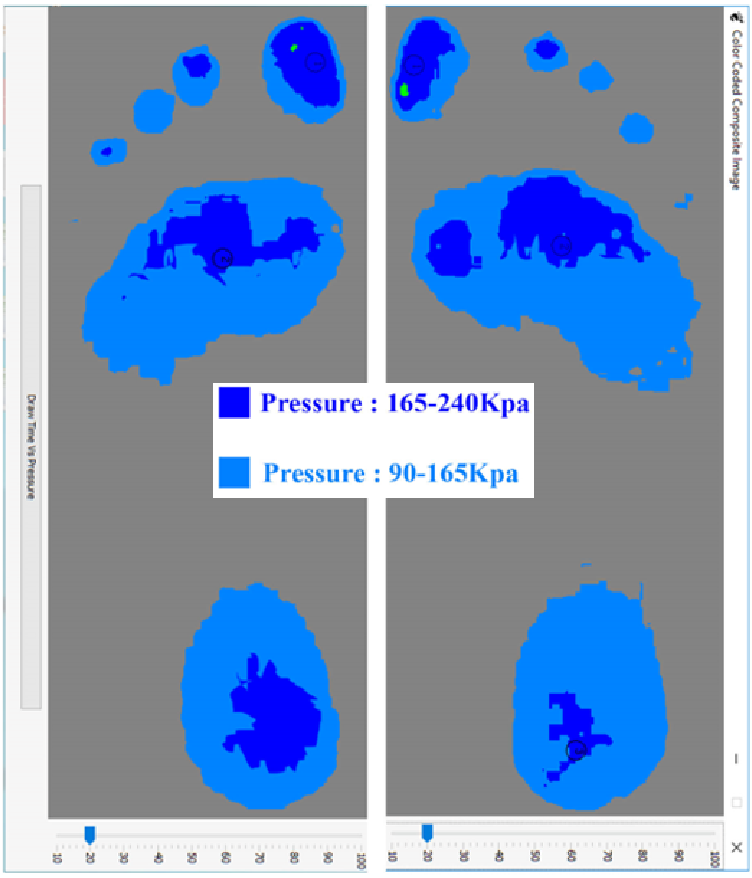


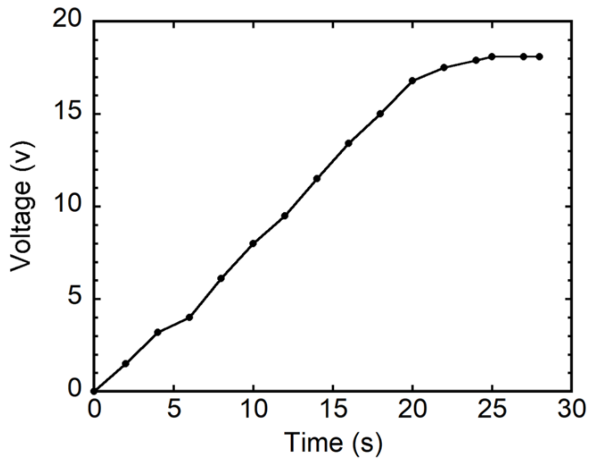
Figure 6. Pressure diagram of left and right legs (Dynamic Pedograph)

Table 1 describes the discrete and pulsating DC voltage during walking. Ten footsteps voltage data was taken. Every footstep showed a variable voltage data as different weight pressure at random. When the piezo disc got the perfect contact on it, it generated more voltage. These results inspired the future study in this sector.

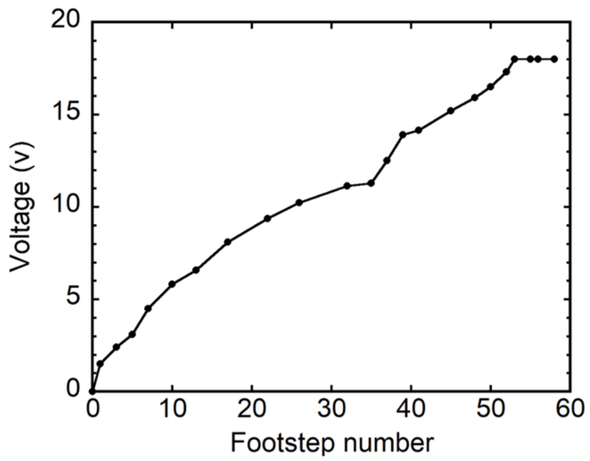
Table 1. Measurement of DC voltage for 10 footsteps (random)

Footstep order at rectified stage (random)	During walking DC voltage (volt)
1st	2.6
2nd	2.0
3rd	1.7
4th	2.8
5th	1.9
6th	1.1
7th	1.4
8th	2.1
9th	1.9
10th	2.8

Figure 7 shows the connection resistance, contact resistance and wire resistance possessed the greater reduction value. During walking, the voltage gradually increased from 0 to 18 V in 25 s as shown in Figure 7(a). After 53 footsteps, continuous and fixed DC voltage stopped at only 18 V at heel area as shown in Figure 7(b).



a)



b)

Figure 7. (a) Voltage vs time; (b) Voltage vs footstep number

It is very important where and how the foot pressure is distributed. During walking or running, foot pressure varies for different parts of the shoe. Different areas, like heel, toe, waist area and mid foot showed different results. Here, heel was chosen and discrete value was taken. It showed the highest voltage value, 43 V (AC). It varied for every footstep. It normally depends at which angle the foot exerts pressure on the shoe heel. When the highest pressure was at the exact point of the disc, the highest voltage value was measured. If the highest pressure was on the disc but not at the exact point, the highest voltage value could not be obtained. It also depends on whether the person is walking or running. Most of the time the shoe design and structure show different results. The centre of gravity controls the foot pressure on the shoe. Though the heel area is narrow, the highest pressure falls on that area. When standing in shoes, more body weight is on the heel and hence it shows the highest output. Again, the data drastically decreased after connecting the capacitor. Here, fixed DC voltage was generated. The bridge rectifier lessened the voltage value. Capacitor again decreased the rectified voltage.

Figure 8 shows a nearly linear curve of voltage vs. the flow of the current at the storage stage in the capacitor. It follows Ohm's law. Here, the resistance was about 10 MΩ. It shows higher resistance because of different sources of resistance, like contact resistance, wire resistance, test machine resistance and soldering resistance, as result increased the resistance and hence lowered the current flow. The higher voltage was found but the current was very low. As a result, it produced small power output and lower energy values. This small power output could activate only a single LED light. Moreover, when the power was transferred to the other circuit, it showed feeble possibility. Highest voltage was found to be 18 V with the highest current value at 2.45 µA, as shown in Figure 8. In order to get a smooth and easily understandable value, the simulated and round figure was taken.

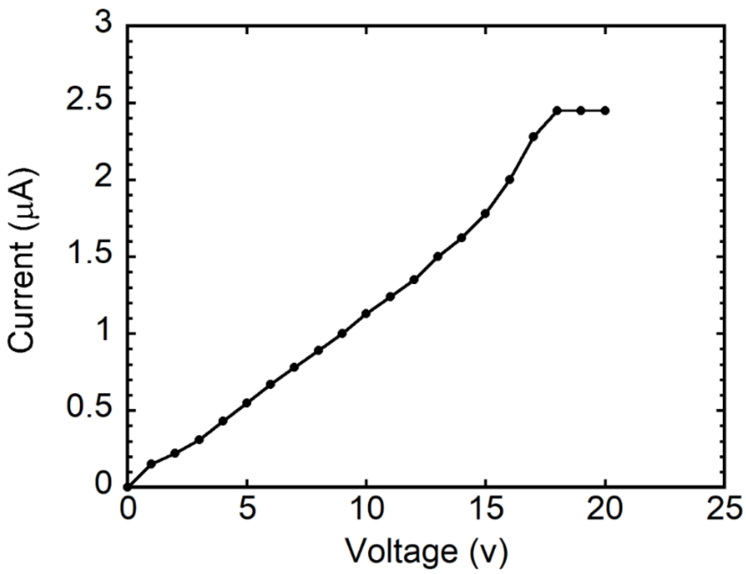


Figure 8. Voltage vs. current (V-I) curve

Mathematical description

Energy was calculated with the following mathematical equation; the highest value produced was taken.

$$E = 0.5 \times C \times V^2 \quad (1)$$

where E = energy, C = capacitance and V = voltage for 53 footsteps.
Eneregy (E) was calculated using joule units for 53 footsteps. Here, C = 22 µF and V = 18.6 V and hence:

$$E = 0.5 \times 22 \times (18.6)^2 = 3805.56\ \mu J = 3.80556\ mJ \quad (2)$$

Finally, 3.80556 mJ for 53 footsteps during walking were obtained. For a single step is following,

$$E = 3.80556 \div 53 = 0.0718\ mJ/step = 0.0000718\ J/step \quad (3)$$

Power was calculated with the following mathematical equation,

$$P = V \times I \quad (4)$$

where I = current, 2.45 µA, V = voltage, 18 V, t = time, 25 s, P = power, unknown. Hence,

$$P = 18 \times 2.45 = 44.10\ \mu W \quad (5)$$

Energy was

$$W = P \times t = 44.10 \times 25 = 1102.5\ \mu J \quad (6)$$

For one minute, W = 2646 µJ and for two hours, W = 317.52 mJ. On average, a person walks 8000 steps per day (two hours) [21].

CONCLUSION

In this research, the electrical energy during walking was harvested. The highest energy value that our present circuit-footwear design has generated was 317.52 mJ for two hours per day. The specially designed shoes showed the pressure threshold extended into the electricity as well *I-V*. It is obvious that the pressure gives rise to localized energy levels in the PZT. It is ensures a better alternative technique of harvesting non-conventional energy. Applications include a promising energy conversion capability for electrical energy. Further improvement (design authentication and proper monitoring analysis) could bring more power from alternative non-conventional energy sources in the future. The non-conventional energy sources could be used for charging small electronic devices.

Author Contributions

Conceptualization – Abdulla-Al-Mamun M, Hossain MA, Paul AC; methodology – Abdulla-Al-Mamun M, Hossain MA; formal analysis – Abdulla-Al-Mamun M, Hossain MA; investigation – Hossain MA; resources – Abdulla-Al-Mamun M, Hossain MA; writing-original draft preparation – Abdulla-Al-Mamun M, Hossain MA, Paul AC; writing-review and editing – Abdulla-Al-Mamun M, Hossain MA; visualization – Paul AC; supervision – Abdulla-Al-Mamun M. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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