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Article

Development of Smart Shoes Using Piezoelectric Material

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***Abstract*— The consumption of low-power electronic devices has increased rapidly, where almost all applications use power electronic devices. Due to the increase in portable electronic devices' energy consumption, the piezoelectric material is proposed as one of the alternatives of the significant alternative energy harvesters. This study aims to create a prototype of "Smart Shoes" that can generate electricity using three different designs embedded by piezoelectric materials: ceramic, polymer, and a combination of both piezoelectric materials. The basic principle for smart shoes' prototype is based on the pressure produced from piezoelectric material converted from mechanical energy into electrical energy. The piezoelectric material was placed into the shoes' sole, and the energy produced due to the pressure from walking, jogging, and jumping was measured. The energy generated was stored in a capacitor as piezoelectric material produced a small scale of energy harvesting. The highest energy generated was produced by ceramic piezoelectric material under jumping activity, which was 1.804 mJ. Polymer piezoelectric material produced very minimal energy, which was 55.618 mJ. The combination of both piezoelectric materials produced energy, which was 1.805 mJ from jumping activity.**

***Keywords*— Piezoelectric; Smart Shoes; Polymer; Ceramic**

I. INTRODUCTION

The piezoelectric material is one of the nanotechnologies that scientists had tested for its usefulness. For example, piezoelectric can be found in many places, such as Japan's subway, dance floor, and football stadiums. The word 'piezo' means to press or squeeze. Piezoelectric materials can produce electrical energy when there is some pressure or mechanical stress applied to them. Jacques and Pierre Curie discovered piezoelectricity when an electrical charge was produced from crystals as pressure was applied. Then, they had assumed this phenomenon as the piezoelectric effect [1]. There are two types of piezoelectric effect: direct piezoelectric effect and inverse piezoelectric effect. The direct piezoelectric effect implies the conversion of mechanical stress into electrical charge. The metal plate compresses the ceramic piezoelectric material to produce electric energy. The charge of positive and negative are collected using a metal plate to produce voltage [2]. Next, the inverse effect converts electrical energy into mechanical energy. The metal plate of piezoelectric ceramic material contracts or expands when electrical energy is applied. The examples of devices that applied this effect are piezoelectric acoustic devices, such as speakers and buzzers, while non-acoustic devices are motor and actuators. When these devices have used the inverse piezoelectric effect, it generates and creates acoustic sound waves. Piezoelectric ceramics is another example of piezoelectric materials often used until now [3]. It has high efficiency in transforming mechanical energy produced by pressure into electrical energy.

Moreover, it also easy to get at a low cost [4] and widely used due to its excellent performance. However, piezo ceramic is toxic and brittle [5]. Bischur et al. state that polymer piezoelectric can change mechanical stress into electrical energy. Both of them realize that polymer piezoelectric has higher polarization, resulting in better performance of converting energy. They made conclusions that polymer piezoelectric is more advance than the ceramic piezoelectric material [6]. Piezo polymer can produce high impact resistance and high mechanical strength than piezo ceramic. It also indicates better sensor applications than piezo ceramics [7]. This efficiency depends on the properties of piezoelectric material, thickness, and the force affecting the piezo. Besides, the output of voltage produced may be different according to the temperature of the piezoelectric material. The vital fact about developing the piezoelectric generator is challenging. Hence, they have a poor source of characteristics, which are high voltage, low current, high impedance, and low power output [8].

This research focused on developing smart shoes with three different designs using piezo ceramic, polymer, and a combination of piezoelectric materials on various physical activities, such as walking, jogging, and jumping. The piezoelectric materials were implemented into the soles of shoes. As the person started to walk, jog, and jump, the vibration from physical activities' pressure converts mechanical stress into electrical energy. The electrical energy generated by the piezoelectric materials can be used as a source of energy for electrical power devices. Subsequently, the electrical energy will be stored as a charge in a rechargeable battery to charge a mobile phone [9]. It also does not need any external sources to generate electricity from pressure and vibration, called self-generating. Besides, it is eco-friendly and does not cause any pollution to the world. The disadvantages of piezoelectric material are that it does not generate any electricity for the static condition, sensitive in high temperatures, and not suitable for large-scale energy harvesting due to its low power output. When there is no pressure or vibration exerted on the piezoelectric material, there is no charge produced. Then, it gives a high voltage but very low current. The output of voltage produced may be different according to the piezoelectric material's temperature [8].

II. METHODOLOGY

A. The circuit design of smart-shoe embedded with piezoelectric materials

First and foremost, piezoelectric material was connected in a parallel circuit to increase voltage and current output. A full-wave bridge rectifier will convert AC into DC. Hence, piezoelectric material creates AC. Diode bridge rectifier also prevents current from flowing back into the piezoelectric material. All the parallel circuits were connected to a 25V 1000μF capacitor because the capacitor acts as energy storage. The capacitor has a similar function as a battery, which can store electrical energy. The capacitor can store a small amount of electricity, whereas the battery can store a larger energy amount. In this study, the amount of energy produced by piezoelectric materials was too small. Hence, the capacitor was chosen as a storage device. In this study, the LED was lighted up, showing that the current was flowing through the circuit. Then, the output of voltage and current was measured by using a multimeter.

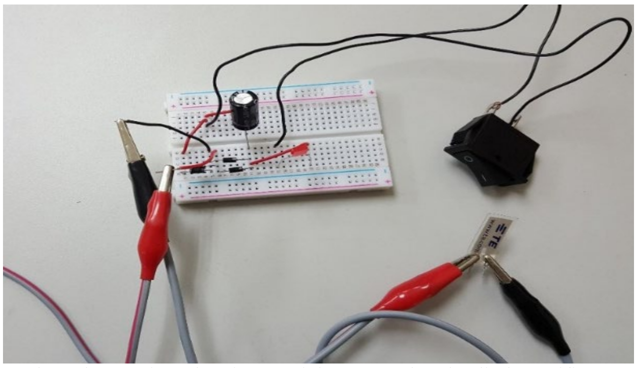

Fig. 1 The polymer piezoelectric material connected to the diode rectifier

Subsequently, the prototype of smart shoes was designed in three types, including Design A (smart shoes with ceramic piezoelectric material), Design B (smart shoes with polymer piezoelectric material), and Design C (smart shoes with a combination of polymer and ceramic piezoelectric material). The prototype of smart shoes is shown in Figure 2. The piezoelectric materials were placed into the soles of shoes at the heel area. Hence, the heel area exerted more pressure compared to the toes area. Ceramic piezoelectric materials were covered with a sponge to avoid damage when pressure is exerted on them. To run the experiment, the piezoelectric disc must have the same piezoelectric constant, C. The thickness of the piezoelectric ceramic disc is 2.0 mm, while the diameter is 20 mm.

Moreover, the piezoelectric polymer film's thickness is 28μm, while the diameter is 10 x 2.5mm. The number of ceramic piezoelectric materials used in designs A and C were 20 pieces with a surface area of 20mm. The number of polymer piezoelectric material was two pieces for design B and C. The sole of smart shoes for design A and C was prepared into two layers to maximize the space for piezoelectric materials.

Fig. 2 Piezoelectric materials placed into the sole of shoes at the heel area

Next, the other parameters considered were the pressure exerted from different types of physical activities. Three different physical activities were carried out during the experiment: walking, jogging, and jumping. The same person was chosen to conduct physical activities for the same duration of time. Each activity was carried out for 15 minutes. For comparison of all designs, only jogging was conducted. The data were recorded throughout the activities. The pressure from the physical activities exerted on the piezoelectric materials produce electrical energy and was stored in the capacitor. Last but not least, the capacitor was successfully tested using the Gamry software instrument. The software functions to analyze the voltage and current cycle in the capacitor charged during physical activities.

The results were obtained from the calculation of the energy produced, using the formula of Power, *P,* which is the product of Current, *I* and Voltage, *V* produced as the capacitor is charging during the stepping process, given by Equation (1).

$$P = IV \tag{1}$$

The capacitance value is obtained from the charge and discharge graph of the capacitor. The formula to obtain capacitance is given by Equation (2), where I represents the difference between the charging and discharging rate of the capacitor. It can be obtained directly from the graph or by calculating the data at 10 mV/s.

$$C=2I/(Scan\ rate) \quad (2)$$

Scan rate is the rate of change of potential with time in the unit of mV/s. Scan rate at 10 mV/s allowed slow processes to occur, where many charges move into the capacitor. Scan rate also influenced the graph of charging and discharging the capacitor. The amount of electric charge stored in the capacitor is proportional to the voltage given by equation (3). Here, Q is the capacitor's charge, C is the capacitance, and V is the voltage between the device's terminals. The energy stored in the capacitor can be calculated using equation (4).

$$Q=CV \quad (3)$$

$$E=1/2\ CV^2 \quad (4)$$

III. EXPERIMENTAL RESULTS

A. *Types of physical activity*

In this parameter, smart shoe design A (piezo ceramic only) was tested on different physical activity types. The pressure produced during different physical activity types, walking, jogging, and jumping exerted on smart shoes may affect the power generated. Thus, the power was generated as an output result. The recorded data for different types of physical activity are shown in Table I and Figure 4. Based on Figure 3, more energy was generated when more strenuous physical activity was performed. Hence, walking obtained less energy (0.146 mJ) compared to jogging (1.376 mJ) and jumping (1.804 mJ). The graph recorded the highest energy of 1.804 mJ at the jumping activity.

TABLE I
POWER AND ENERGY GENERATED BY PHYSICAL ACTIVITIES ON DESIGN A

Types of Physical Activity	Average Voltage, Vavg (V)	Average Current, Iavg (μA)	Power, P (mW)	Energy, E (mJ)
Walking	1.368	0.396	0.0005	0.146
Jogging	3.624	1.272	0.0046	1.376
Jumping	4.146	1.466	0.0060	1.804

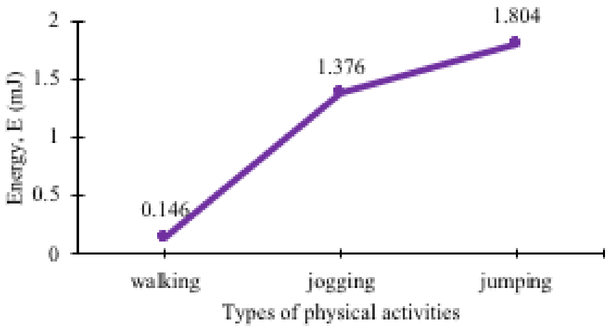

Fig. 3 Energy generated against physical activities (Design A)

Next, this parameter was tested on the smart shoe design B, which applied piezoelectric polymer only. The same procedure was performed, whereby the pressure produced during walking, jogging, and jumping exerted on the smart shoes were recorded. The physical activities affected the power generated as the output results. The recorded data for different types of physical activity are shown in Table II and Figure 4. A similar trend to the graph in Figure 5 was obtained for the piezoelectric polymer. However, the amount of power and energy produced was lesser than piezo ceramic. According to the specifications, the piezo polymer is a flexible structure. Any pressure that bends the piezo polymer creates a very high strain on the structure, generating a high voltage. Vibration energy is more suitable for bending the piezo polymer in producing energy. However, in this study, pressure from physical activities exerted on the piezo polymer is more constant pressure with no vibration.

Furthermore, the pressure exerted by physical activities cannot bend the piezo polymer. This specification explained why the energy generated during this study was very low (nano joules). Besides, the number of piezo polymers used in this study was only two pieces compared to the piezo ceramic of 20 pieces. The reason for using a minimal amount of piezo polymer is due to the costly price of the piezo polymer. Note that the highest energy was produced by jumping activity, which recorded 55.618 nJ. If we compare the energy generated by piezoelectric ceramic and polymer for similar activity (jogging), the piezo polymer produced 1.376 mJ less than piezo ceramic.

TABLE II
POWER AND ENERGY GENERATED BY PHYSICAL ACTIVITIES ON DESIGN B

Types of Physical Activity	Average Voltage, Vavg (V)	Average Current, Iavg (nA)	Power, P (nW)	Energy, E (nJ)
Walking	0.017	0.308	0.0052	11.135
Jogging	0.028	0.312	0.0087	30.658
Jumping	0.036	0.412	0.0148	55.618

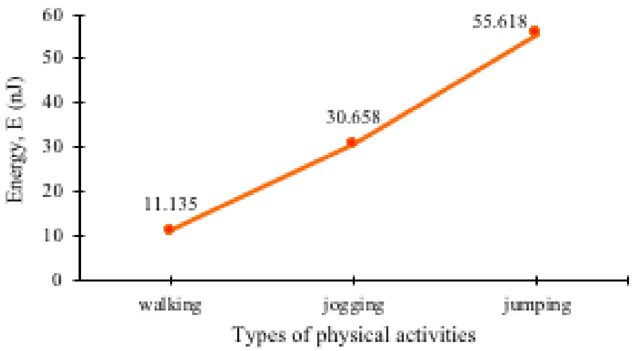

Fig.4 Energy generated against physical activities (Design B)

The physical activity types were then tested on the smart shoe design C, a combination of ceramic piezo and polymer piezo. These physical activities affected the power and energy generated as the output results. The recorded data for various types of physical activity are shown in Table III and Figure 5. Walking activity obtained less energy (0.146mJ) than jogging and jumping, which was 1.380mJ and 1.805mJ, respectively. The energy generated increased as more strenuous physical activity was performed.

TABLE III
POWER AND ENERGY GENERATED BY PHYSICAL ACTIVITIES ON DESIGN C

Types of Physical Activity	Average Voltage, Vavg (V)	Average Current, Iavg (µA)	Power, P (mW)	Energy, E (mJ)
Walking	1.370	0.398	0.00055	0.146
Jogging	3.628	1.284	0.00465	1.380
Jumping	4.148	1.468	0.00609	1.805

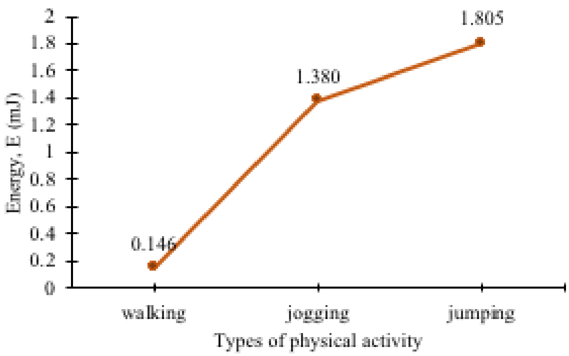

Fig. 5 Energy generated against physical activities (Design C)

B. Types of smart shoe's designs

Smart shoes are prepared in three designs, Design A (smart shoes with ceramic piezoelectric material), Design B (smart shoes with polymer piezoelectric material), and Design C (smart shoes with a combination of polymer and ceramic). In this study, three designs (Design A, B, and C) were tested using only jogging. The purpose is to compare the amount of power generated when two types of piezoelectric materials were combined, as shown in Table IV and Figure 7 below. Based on Figure 6, the power generated from Design A (0.0046mW) and Design C (0.0047mW) showed a minimal difference of 0.0001 mW. The combination of piezo polymer and ceramic did not improve much of the energy generated. Even though piezo polymer is a better sensor than ceramic, the piezo polymer's pressure was not suitable. It required a vibration type of pressure rather than constant pressure to generate electricity. Design B recorded the lowest power generated at 0.0000000087 mW.

TABLE IV
POWER AND ENERGY GENERATED BY DESIGN A, B, AND C

Types of smart shoe's designs	**Average Voltage, Vavg (V)**	**Average Current, Iavg (µA)**	**Power, P (mW)**	**Energy, E (mJ)**
A (ceramic piezo only)	3.624	1.272	0.0046	1.376
B (polymer piezo only)	0.028	0.000312	8.7×10^{-9}	3.06×10^{-5}
C (polymer and ceramic piezo)	3.628	1.284	0.0047	1.380

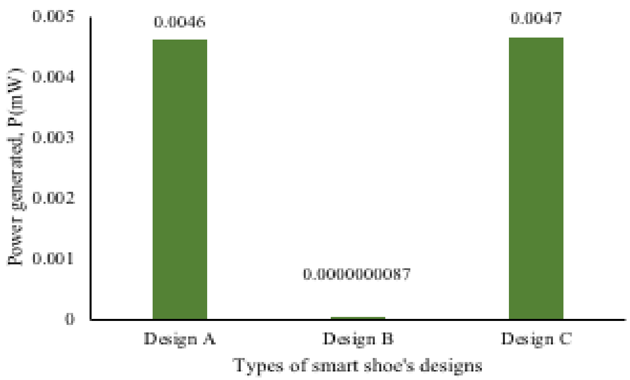

Fig. 6 Power generated against types of the smart shoe (Design A, B, and C)

C. *Energy stored in the capacitor*

Given the small amount of energy generated, the capacitor is used as energy storage instead of a battery. A capacitor is also used to stock the electric charge so that when the person is not in motion, the power is continually supplied. The capacitor was tested using Gamry software after jogging activity. Both capacitor electrodes were connected, and the software scanned the capacitor until three cycles, producing a graph of cyclic voltammetry, as shown in Figures 7, 8, and 9.

TABLE V
ENERGY STORED IN THE CAPACITOR AFTER JOGGING

Experiment	**Capacitance, C (µF)**	**Energy, E (mJ)**
Jogging by using smart shoe's design A	209.58	1.376
Jogging by using smart shoe's design B	78.21	0.0000306
Jogging by using smart shoe's design C	209.62	1.380

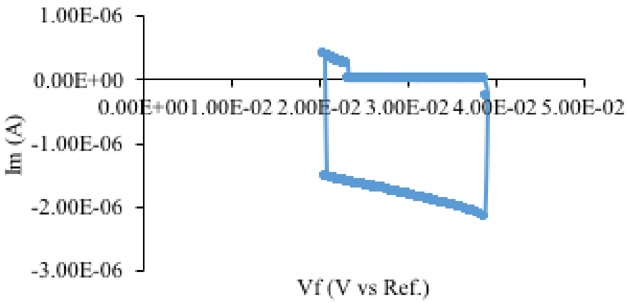

Fig. 7 Cyclic Voltammetry of 25V 1000µf Capacitor (Design A)

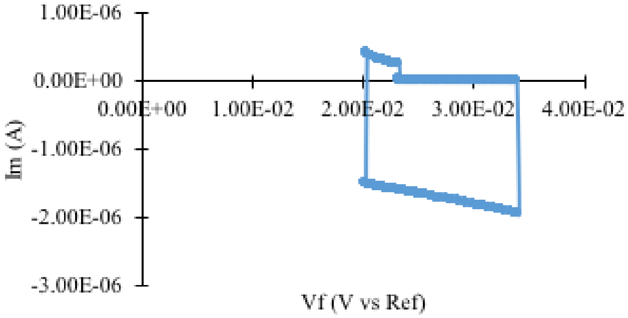

Fig. 8 Cyclic voltammetry of 25V 1000µF Capacitor (Design B)

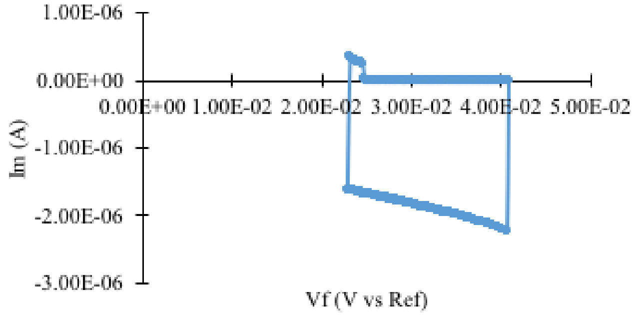

Fig. 9 Cyclic Voltammetry of 25V 1000µF Capacitor (Design)

Figures 7, 8, and 9 showed the result of charge produced after jogging activity within 15 minutes for Design A (ceramic piezo only), Design B (polymer piezo only), and Design C (a combination of ceramic and polymer piezo). Based on cyclic voltammetry graphs, the current flowing through the capacitor was plotted versus the voltage that was swept over a given voltage range.

Based on the theory, for an ideal capacitor without equivalent series resistance (ESR), the shape of CV would be a rectangle [10]. The above three graphs showed a rectangular shape plot. However, they were not exactly rectangular in shape as there was leakage of current from the device. The value of the charge in the capacitor is equal to the area of the graph. After several cycles of charging, the area of the graph became bigger. From the result, the value of capacitance was increased after each trial when the experiment was performed using three different designs of smart shoes.

In Table V, the most significant energy generated and stored in the capacitor was smart shoe Design C, which consists of ceramic and polymer piezoelectric materials (1.380 mJ). Design A recorded 1.376 mJ, while Design B was also generated and stored in the capacitor. However, the energy stored was too small. It shows that the power generated by ceramic and polymer piezoelectric material was collected and stored in the capacitor. The reading of capacitance for cyclic voltammetry of 25V 1000µF Capacitor (Design A, B, and C) were 209.58µF, 78.21 µF, and 209.62 µF, respectively. Design C showed the highest reading of capacitance than Design A and B from the results obtained.

IV. CONCLUSIONS

In this study, the smart shoe prototype was successfully developed and tested. It can generate electricity without the consumption of fossil fuels. It can also conserve the usage of electricity for further use. However, the amount of energy generated by the piezoelectric materials is minimal and needs improvement. Ceramic material is easily broken compared to polymer piezoelectric material, which is more flexible. The data recorded for Design A shows that whenever a strenuous activity, such as jumping, was performed for 15 minutes, the amount of energy produced was 1.804 mJ. If the duration of physical activity is added up to 1 hour, the potential energy generated will be 7.216 mJ. Next, the power generated by Design B recorded the lowest, which was 0.0087 nW. It is too low and requires a vibration type of pressure. The polymer piezoelectric material should be bend to have a higher output than placing constant pressure on it. Among the three designs of prototype smart shoes, Design C recorded the highest energy and power, which were 1.380 mJ and 0.0047 mW, respectively, by a single person. A more efficient smart shoe can be designed by adding the number of piezoelectric materials to increase the surface area so that more mechanical stress can be transferred to the piezoelectric material.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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