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Finite Element Analysis of PZT-Integrated Shoe Sole for Electrical Energy Harvest

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Abstract: This paper proposes a new technique for electrical energy harvesting from vibration energy generated in a shoe sole. In this technique stacked lead zirconate titanate (PZT) material was integrated into shoe sole. The PZT and the shoe sole system have been modelled and validated using the ABAQUS software. The sensitivity of the PZT part was found to be 0.0694 mV µm µN^{-1}. Similarly, the shoe sole model was in accordance with strain invariants which is directly based on the stretch ratios and was classified as hyper-elastic material. A statistical technique was used to obtain an average size of 28.0727 cm for the shoe sole computed from data of standard adult shoe sizes. The two parts were assembled together to function as a single unit. Our research shows that, as the applied force increases in PZT material, the output voltage also increases. For this reason, PZT material was integrated in to the shoe sole. The shoe sole is an area where the weight of human body is concentrated for optimal electrical energy harvesting. Furthermore, we have investigated that, for the pressure/force applied to the PZT material within a short time (approximately 1second), the electric potential attends its approximate maximum value of 0.016 volt. The total amount harvested will be (0.016n) volt, where n is the number of the stack PZT material. Thus, the amount of electrical energy harvested depends on the weight of the person wearing the shoe at a particular time and the number of the stack PZT material integrated into the shoe sole. Additionally, the research shows that, the output voltage generated by PZT material is independent of the size of the material. The output from each individual PZT unit was cascaded to obtain the total electrical energy harvested. The total electrical energy harvested was transferred wirelessly to the target electronic devices such as miners' lamp, military gadget, etc. Therefore, the proposed technique will serve as a solution to power miners' lamp, military electronic gadget (compass, radios, lighting etc.), lighting in situation where energy cannot be harvested from solar, during mining in underground tunnels and during movement in a battlefield especial when expecting opponent attack

Keywords: Finite element method, Electrical energy harvest, Stack PZT-Integrated shoe, Optimization, Random variable, Stack PZT, Vibration energy.

1. Introduction

Advancements in technology result in the high demand for energy to power micro-nano electronic sensors, electromechanical systems, micro-nano embedded systems etc. [1-2]. As a result energy harvesting from immediate environment is unavoidable. Energy harvesting is a technique for extracting energy from immediate environment, for example from wind energy, solar energy, vibration, heat, noise etc. In fact, harvesting energy is more important than conserving energy. Energy can be obtained from several sources, however clean energy has become an interest to many researchers. Fossil energy is becoming a global threat to human lives and the environmental [1]. As a result, global Sustainable Development Goals (SDG) were introduced to give a roadmap on moving from conventional dangerous sources of energy to clean sources of energy [1-2].

Many sources of energy such as solar energy, hydro energy, wind energy etc. are considered to be clean sources. The most popularly known technique for ambient energy harvesting is harvesting electrical energy from solar energy. Although several other techniques for energy harvesting are available, which include thermal gradients, energy generated from human body activities, electromagnetic, gravitational field action and fluid flow [3]. However, these source of energy depend mainly on the condition of the environment at a particular time and the techniques for harvesting the energy from these sources. For this reason an alternative source of energy, which is independent of the environmental condition should be the solution. As a result, in recent years the field of energy harvesting which is independent of the environmental conditions is one of the active research areas receiving ever growing research attention [3-4] so as to design self-sustaining electronic and electromechanical systems. Indeed eliminating over dependency on limited life span and dangerous systems such as battery, nuclear etc. [4].

Researchers have proposed many techniques for harvesting energy from the immediate or ambient environment to power electronic and electromechanical systems.

According to statistics of international energy consumption, approximately 4 % of energy generated is been lost due to vibration, friction, sound, etc. [5]. Based on this statistic, techniques for transforming these forms energy in to useful energy are highly needed. The most abundant source of energy which is independent of environmental conditions is vibration energy [6]. This form of energy is generated unknowingly by human activities every day [1, 6]. However, the technique to collect this form of energy and convert it into useful form of energy remains unsolved. The most recent techniques used to collect vibration energy and convert it to useful form are, using piezoelectric, electromagnetic and electrostatic devices. The safest technique for humans for converting mechanical energy to clean electrical energy is using piezoelectric devices [7]. Furthermore, PZT systems of energy harvesting is considered to be the simplest method of electrical energy harvest [8]. This is due to the fact that, the mechanical stress at the surface of the material is directly converted into electrical energy [7-8]. In fact, it is 99 % health hazard free and environmentally friendly due to zero emissions [9]. Conversely, some methods of transmitting energy in general from source to destination are not safe to human lives. Although piezoelectric material is an active transducer, but its application to solve immediate environmental problems to enhance the quality of human lives is still in its early stage [10].

In the literature, many techniques for energy harvest have been proposed and several attempts were made to harvest vibration energy. In [6] harvesting electrical energy from vibration energy using piezoelectric material to power electric vehicles based on feedback energy mechanism of unchanged vehicle suspension system from segmented circumferential gear structure have been proposed. In this technique, the vibration energy generated from vehicle was used to power on-board electrical devices and charge a battery. The main drawback of this technique was low energy conversion efficiency. As a result, the technique was complex for harvesting vibration energy. However, modelling and simulations proof that high conversion efficiency of vibration energy is feasible using piezoelectric materials [11]. PZT based micro power generator for glove structure have been proposed by [12]. Fibres of PZT materials were used in the development of the device [12]. The PZT fibres are arrange in the composite structure pointing the same direction. Based on this arrangement output voltage level was raised up to 6 V. In fact, the level of voltage achieved could power wearable micro-nano electronics systems. But on the other hand integrating the PZT fibres in brittle material will lead to the breaking up of the fibres. For this reason, the technique cannot be generalised for all the structures.

A survey on various techniques of energy harvesting architecture of sensor network system was proposed by [13-14]. In the work of the authors in [15], PZT model was used to derive energy from the surrounding specimen under investigation. The model obtained as reported by [15], provided an easy way for determining the optimal size and vibration level design procedure to achieve optimal energy harvesting to power electronic systems. Furthermore, experimental validation was conducted by the authors in [15] to confirm the accuracy of the model developed. An alternative PZT bending system was proposed by authors in [16]. The system designed was based on impact generated by a body with appreciable mass in motion. Furthermore key parameters affecting the performance of the system was analyzed in order to optimize the system [16-17]. Synthesis of PZT nano crystalline particles and analysis of its electrical properties for micro electronic system design was proposed by [18]. Moreover, sol-gel modified process approach was introduced during the PZT nano crystalline particles synthesis. The effect caused by change in temperature and load variation of PZT-5A were investigated by the authors in [19]. The research outcome shows that the output voltage of the PZT-5A material varies inversely with the temperature and directly with loading [19]. Application of PZT model in prosthetic legs movement at low frequency have been proposed by [20]. Chemical solution and micromachining based PZT cantilever for compensating stress have been fabricated by [21]. Furthermore, finite element analysis of PZT based integrated micro-nano sensors for medical applications were investigated by [22]. Similarly, PZT nano position control were proposed by [23].

Research effort have been devoted in energy harvesting, however, there is very little effort devoted to the issue of harvesting electrical energy from vibration energy to solve from problems faced by miners, military, etc. in powering electronic devices. For this reason, improved energy harvesting independent of environmental conditions is the solution. PZT harvester is one of the effective harvesters as it converts mechanical energy directly into electrical energy. To fill this gap, in this paper we propose~~d~~ a lead zirconate titanate (PZT)-integrated shoes for energy harvest to power miner's lamp, military electronics devices and other important electronics devices during an emergency in an environment where there is no power source and zero possibility of harvesting energy from solar. As a result, this research will serve as a better way for solving the problem of powering important electronics devices during an emergency in an environment where there is no power source and zero possibility of harvesting energy from other alternative sources. Another advantage of PZT energy harvest, is that external and internal factors such as electromagnetic waves ~~has~~ have no effect on the material [9]. The rest of the paper is organized as follows. The paper is organized in five (5) sections. In section one (1), introduction and existing research on electrical energy harvesting from vibration energy using PZT material were presented. In Section two (2), system idea and concept was presented. Finite element (FE) modelling, validation and optimization of PZT-integrated shoe for energy harvest to power miner's lamp, military electronics devices (radio, electronic compass, electronic watches etc.) were presented in Section (3). Section (4) presents result and analysis obtained in Section (3). Concluding remarks were presented in Section (5).

2. System Idea and Concept

The main function of the system is to harvest electrical energy from vibration generated during movement by human beings from shoes. For this reason the PZT material is integrated into the shoes as it's the place where the maximum pressure is generated in human body while moving. We investigated in depth using finite element method to harvest optimal amount of the electrical energy from the vibration energy. We used stack PZT material integrated into the shoes of the target person so as get maximum amount of the electrical energy. The stack PZT material are connected in parallel and the electrical energy generated is transmitted wirelessly to the target electronic system as shown in Fig. 1. The idea of the wireless transmission will allow the person using the shoe to have free and comfortable movement. In fact, the energy generated can be stored in a remote bank for other uses.

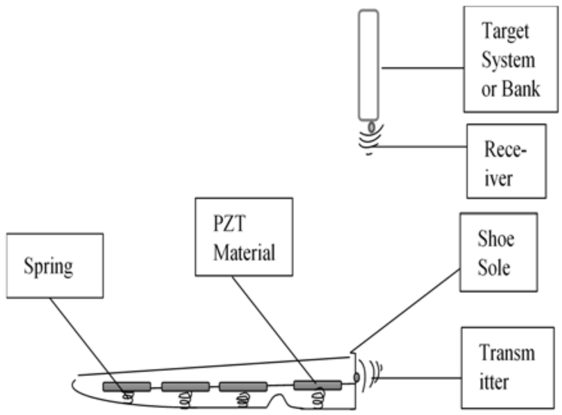


Fig. 1. PZT-integrated shoe sole for electrical energy harvest design concept.

3. Finite Element Modelling, Validation and Optimization of PZT-Integrated Shoe Sole

ABAQUS software package (ABAQUS 6.14 CAE/CEL, Dassault Systemés, Pawtuckett, Rhode Island, USA) is one of the flexible, commercially available and famous finite element analysis software. For this reason the software it is commonly used in modelling, simulation, finite element analysis and data validation of complex engineering analysis. The software was chosen for numerical electrical energy harvesting from vibration energy and validation of data obtained based on the current literatures. Furthermore, the software gives the solution of complex equations generated during the analysis. We have reported that various attempts have been made to harvest electrical energy from vibration energy using PZT material, their disadvantages outweigh their advantages which has been highlighted in Section I of this paper. For this reason, we proposed a noble technique for harvesting electrical energy from vibration energy using PZT-5H integrated in a shoe sole. Furthermore, the electrical energy harvested will be transmitted wirelessly to the target device. The modelling consists of the following.

3.1. Finite Element Modelling and Electric Potential Analysis of the PZT Part of the System

The PZT part of the system works based on a phenomenon known as piezoelectricity. The PZT part produces an output voltage proportional to the pressure transmitted to the shoe sole of the person using the system via his feet. The output voltage generated is associated with asymmetrical crystalline nature of the PZT material [24]. The PZT part of the system was modelled numerically in accordance to PZT general constitutive equation given by (1) in tensor and vector form.

$$\begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{pmatrix} + \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \quad (1)$$

Since the PZT material was used as sensor for electrical energy harvest not actuator (1) becomes,

$$\begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{pmatrix}, \quad (2)$$

where D, d, ε and E are the electrical polarization vector, piezoelectric coefficient matrix, stress vector, electrical permittivity matrix and electrical field vector respectively.

When force is applied along the polarization axis of the PZT, (2) is simplified to the axial PZT sensor equation as:

$$Q = -d_{33}F \ , \quad (3)$$

where Q is the electrical charge generated, while F and d_{33} are the force applied and piezoelectric charge coefficient, respectively.

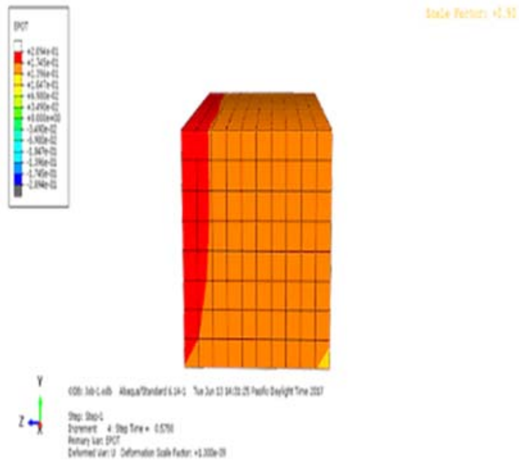
The dimension used was adopted from [11]. As a result it will serve as a process to validate the PZT part model before scaling up the system for electrical energy harvest. Units of consistency were used in the ABAQUS. As a result, all the dimensions used in modelling are based on the micro-MKS system. The piezoelectric material modelled is based on PZT-5H having the piezoelectric, elastic and permittivity features given in Table 1 [11]. The PZT part of the system material properties were defined during the FE modelling process. In SI units, the density of the PZT-5H material is 7500 kg m^{-3}, equivalent to 7.5 × 10^{-15} kg μm^{-3} in the micro-MKS system. The PZT model has been validated by applying force along the poling axis of the PZT part of the system and the corresponding electrical energy.

3.2. Finite Element Modelling of Shoe Sole Part of the System for Electrical Energy Harvest

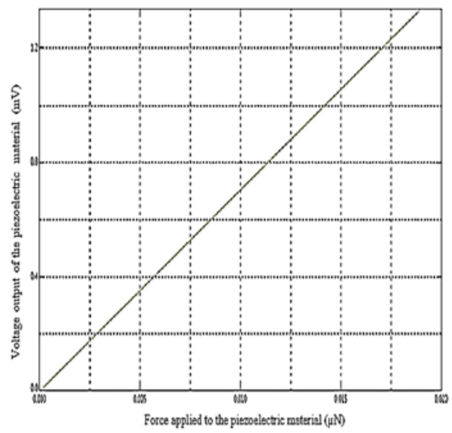
The FEM of the shoe sole was obtained using hard rubber material properties adopted from [25], with an average size of 28.0727 cm computed from data of standard adult shoe size in accordance with the equation given as follows:

$$\mu = \int_{-\infty}^{+\infty} x f(x) dx \, , \quad (4)$$

where x = random variable describing the size of an adult shoe.



(a)



(b)

Fig. 2. (a) PZT material model and (b) Voltage-Force relationship plot for model validation.

The distinctive feature of the model was based on strain energy functions. Moreover, the functions were represented in accordance with strain invariants which directly based stretch ratios. As a result the material was classified as hyper-elastic material. The classical model of nonlinear elasticity is Mooney-Rivlin expressed as:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \quad (5)$$

The model shows a good agreement as compared with tensile test data, however, material stiffening when the value of the strain is very high was not considered. In fact, the model is not sufficient to account for deformation of the material during compression test. For this reason, energy function independent of principal stretches was proposed by [25], expressed as:

$$W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n}(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3) \quad (6)$$

Table 1. PZT-5H Material Properties.

Parameter	Matrix of parameters for polarization along y-axis	Units
Compliance	$\begin{bmatrix} 126 & 841 & 795 & 0 & 0 & 0 \\ 841 & 117 & 841 & 0 & 0 & 0 \\ 795 & 841 & 126 & 0 & 0 & 0 \\ 0 & 0 & 0 & 23 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2325 & 0 \\ 0 & 0 & 0 & 0 & 0 & 23 \end{bmatrix} \times 10^{-4}$	μN/μm²
Stress coefficient	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 17 \\ -65 & 233 & -65 & 0 & 0 & 0 \\ 0 & 0 & 0 & 17 & 0 & 0 \end{bmatrix} \times 10^{-12}$	C/μm²
Dielectric constants	$\begin{bmatrix} 1.505 & 0 & 0 \\ 0 & 1.302 & 0 \\ 0 & 0 & 1.505 \end{bmatrix} \times 10^{-14}$	C/Vμm

From Fig. 3. our shoe sole FE model was in good agreement with [25] based on equation (5) and compression test data obtained from ABAQUS.

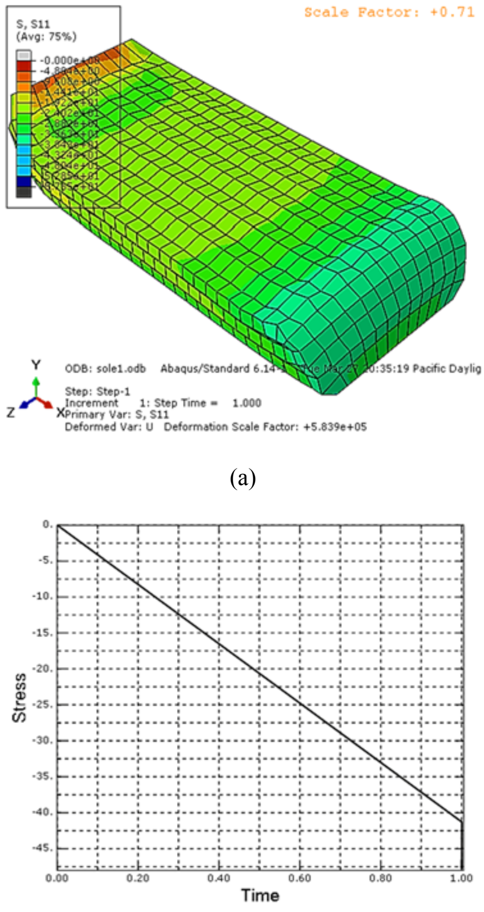


Fig. 3. (a) Shoe sole model and (b) Rate of change of stress during compression test for model validation.

3.3. Finite Element Assembly and Optimization of Shoe Sole and PZT Material for Electrical Energy Harvest

We have modelled and validated the shoe sole and PZT material using FE technique in the previous sub-section of this research work. In this sub-section we present FE assembly of the parts of the system for electrical energy harvest as shown in Fig. 4. Furthermore, the PZT part been an integral part of the system was optimised to harvest maximum amount of electrical energy from the pressure generated by human foot. In our previous researches conducted, we investigated that the electrical energy produced by PZT is not absolutely dependent on the size of the PZT material [22, 24]. For this reason, using stack PZT material generate more electrical energy based on the number of the PZT material stacked together, than using bulk material. However, the electrical current generated by the bulk material is more than that generated by small stack material. Based on this reason, we used stack PZT material and cascaded the output voltage from the individual PZT material as shown in Fig. 5. Indeed several arrangement have been made to obtain optimal amount of electrical energy.

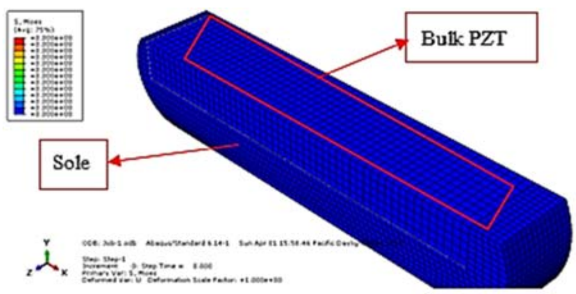


Fig. 4. PZT part and shoe sole part integration for electrical energy harvest.

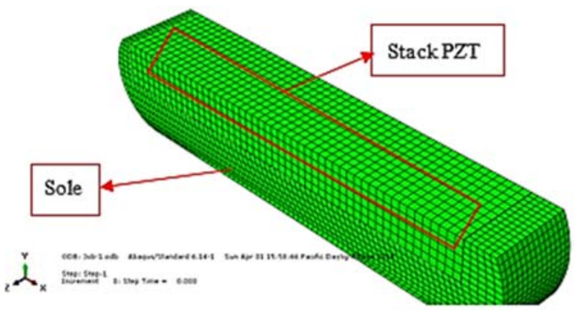


Fig. 5. PZT part optimization for maximum electrical energy harvest.

4. Finite Element Electrical Energy Harvest from PZT Integrated in Shoe Sole

We have modelled, validated and optimized the PZT-integrated shoe sole in the previous section. In this section, electrical energy harvesting using PZT-integrated shoe sole has been conducted using finite element method.

The assembly of the PZT-integrated shoe sole was carried out numerically for electrical energy harvest as shown in Fig. 4. and Fig. 5. Our investigation shows that, as the applied force increases in PZT material the output voltage increases. For this reason, we integrated the PZT material in shoe sole. The shoe sole is an area where the weight of human body is concentrated so that the PZT material will receive the maximum stress for optimal voltage generation. The rate of change of the electric voltage generated by the PZT is shown in Fig. 6. We have investigated that as the pressure/force applied to the PZT material within a short time (approximately 1second) the electric potential attains its approximate maximum value 0.016 volt. The total amount harvested will be (0.016n) volt, where n is the number of the stack PZT material. Thus, the amount depends on the weight of the person using the shoe at a particular time and the number of the stack PZT material integrated in the shoe sole. The relationship between average weight of an adult human being and the electrical potential harvest is shown in Fig. 7. The result obtained above was for a bulk material, our previous researches referenced in this research work investigated that, the output voltage generated by PZT material is independent on the size of the material [22, 24]. For this reason, we optimized the process of harvesting electrical energy by integrating stack PZT material of small size in the shoe sole. The output from each individual PZT unit was cascaded to obtain the total electrical energy harvest. The total electrical energy harvest was transferred wirelessly to the target electronic devices such as miners' lamp, military gadget, etc.

5. Conclusion

This research work demonstrates for the first time the finite element techniques for electrical energy harvest using PZT integrated in a shoe sole. The PZT material and the shoe sole were successfully modelled and validated numerically. The PZT and the sole models were optimized numerically. Further, our investigation established that, the amount of the electrical energy harvested depends on the weight applied to shoe via foot of the person using the shoe, number of stack PZT material integrated in the shoe. Another parameter of interest is that the amount of the electrical energy generated is independent of the size of the PZT material. The main advantage of our PZT energy harvesting technique, is that external and internal factors such as electromagnetic waves has no effect on the material. Furthermore, the technique finds its application in an environment where electrical energy is highly needed. For this reason, our technique will serve as a better way for solving the problem of powering important electronics devices during an emergency in an environment where there is no power source and zero possibility of harvesting energy from other alternative sources.

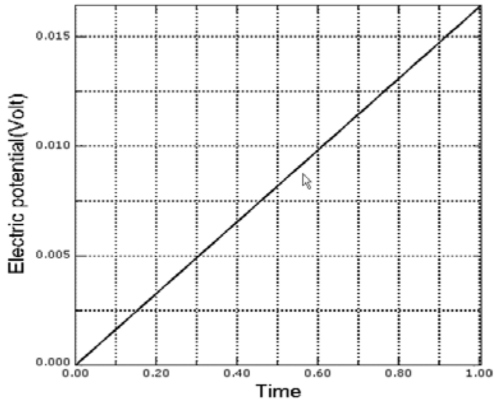


Fig. 6. Rate of change of the electric voltage generated by the PZT.

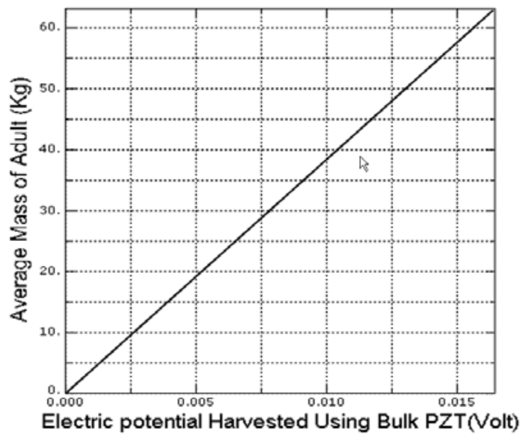


Fig. 7. Relationship between average weight of an adult human being and the electrical potential harvested.

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