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Comparative Analysis of Voltage, Current and Power Produced in a Piezoelectric System from Human Foot Beats

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Authors' contributions

This work was carried out in collaboration among all authors. Authors GCN and UVO conceptualised and designed the study. Authors GCN, PUO and UVO managed the literature searches, fabricated the experimental platform and performed the experiment. Author PUO managed the analyses of the study. Authors UVO and NAO supervised the entire stages of the study including the experiment and verification of results. Authors GCN and PUO wrote the initial draft. All authors reviewed and edited the draft, read and approved the final manuscript.

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ABSTRACT

Aims: This study analysed and compared the amount of voltage, current and power generated in a piezoelectric system from human foot beats.
Study Design: The study was an experimental study which made use of piezoelectric materials together with human loads (weights) from the foot beats of dancers in a dance club, and connected to a rechargeable battery and multimeter. In this system, mechanical deformation was expected to cause conversion of mechanical energy to electrical energy which can be stored in a rechargeable lead acid battery for future use.

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Place and Duration of Study: Awka Anambra State, Nigeria, between November 2018 and February 2020.
Methodology: A sheet of plywood measuring 300 mm x 300 mm x 3 mm thick was placed on a hard wooden board of 300 mm x 300 mm x 25 mm thickwhere twelve piezoelectric sensors were connected in series with foam spring inserted as separators and to aid in returning after deformation. As the dancers step on the platform, multimetr was used to take the voltage and current readings while at the output point Lead acid rechargeable battery could be connected at the output point to store energy generated in the system and orLight Emitting Diodes (LED) and Universal Serial Bus (USB) outputs.
Results: The result revealed that the amount of voltage, current and power generated in the system were principally dependent on the load (weight of dancers in kg). In this case, 1 foot beat of an average 50 kg dancer generated an average of 0.555 mV and 0.063 mA respectively. Whereas, 60 kg and 80 kg dancers generated 0.668 mV and 0.838 mV respectively, and 0.081 mA and 0.087 mA respectively. It further showed that at constant number of foot beats, the amount of voltage, current and power increases as the weight of dancer increases and the lesser the weight the more number of foot beats required to generate the same quantity of electricity. In this case, 100 foot beats of a 50 kg, 60 kg and 80 kg dancer generated 55.5 mV, 66.8 mV, and 84,1 mV of voltage; 6.3 mA, 8.2 mA, and 8.8 mA of current and 349.65 mW, 544.42 mW and 740.08 mW of power respectively.
Conclusion: Implicitly, this system has the potential of alleviating the problem of electricity supply and meeting of vision 2030 Sustainable Development Goals for electricity mix in Nigeria. However, it is mostly required where there are high volumes of human traffic and places that consume minimal amount of electricity, since it usually generates very small amount of energy. In view of this, there is need for a more robust research in this area and increase genuine interest in alternative and sustainable energy research by the Nigerian government.

Keywords: Current; human foot beats; piezoelectric system; power; voltage.

1. INTRODUCTION

Lack of constant electricity due to gap between electricity demand and supply has been identified as the bane of socio-economic and industrial development in Nigeria [1-7], especially for small and medium enterprises [8-11]. Although in the past two decades, power sector has witnessed a lot of reforms in terms of laws, policies and investments [12-17], the sector has not witness any substantial improvement [6], due to systematic lapse in energy policy and historical policy dynamics and structure in Nigeria [18]. This therefore has threatened the chances of meeting the Nigeria's Sustainable Development Goals for electricity mix in 2030 [19].

However, several efforts have been made towards diversifying electricity mix and overcoming the problem of inadequate electricity provision in Nigeria [6,20-22]. These efforts have led to the development and optimisation of different alternative sources of electricity in the country including alternative energy technologies such as solar, tidal, wind, biomass, hydro and geothermal *[*23-26]*.* Unfortunately*,* the sustainability of most of these alternatives still craves for a rethink because, m*ost* of these technologies are not environmentally, economically and socially sustainable [27-31].

In the face of changing demographics and development activities sweeping across the country, the demand for renewable energy has grown so much that it is exceeding the supply due to rapid population growth, industrial development, and domestic usage among households and others. Meeting the growing needs for electricity in these settings requires more energy infrastructure in order to raise current capacity. Despite these concerns, the problem of power outages and limited access to electricity in the country compounded by physical, environmental, management and socio-economic factors [23,32]; demand for a more sustainable system of electricity generation that is reliable, easy and cheap to generate, free from pollution, trigger competiveness and promote decentralisation of energy management [33] for common people and for small scale electricity consumers.

Interestingly, studies have shown that the potential energy in the human body can be converted to electrical energy when the pressure from the body weight of person is applied on the piezoelectric materials through the foot beats;

and in the process causing mechanical deformation in the system [34-38]. Specifically, Abadi et al. [34], Riemer and Shapiro [38], Kuang et al. [39] and Ibhaze et al. [40] concurred that the amount of energy generated in a piezoelectric system directly depends on the applied pressure while the voltage and current maximisation follows directly from the series-parallel connection of the transducers. Aman et al. [41], Rakhe and Singh [42] and Shiraz and Farrukh [43] showed that the amount of power in the system increases as the weight increases. Similarly, Basari et al. [44] found that the output voltage of the piezoelectric device in impact mode is directly proportional to the velocity, whereas the output power is equal to a quadratic function of the same variable. And for the same impact momentum, the effect of the velocity in generating a higher peak output is dominant compared with the mass [44]. Abdul Akib et al. [45], Astudillo-Baza et al. [46], He et al. [47] and Hwang et al. [48] all shared similar concern.

Unfortunately, while frantic efforts have been put in place towards harnessing waste energy in human body in the developed countries and Asia, nothing substantial have been done in this regard in Nigeria. Worse still, the energy that could have been converted and used with minimal cost and effort is left to waste as we walk, run or dance. Thus, the ability to develop a system through which human weight can generate electricity over time at least for small energy consuming appliances and small scale consumers is a milestone towards solving the electricity crisis in Nigeria. Consequently, this study was aimed at analysing the amount of voltage, current and power generated from the human weight in a piezoelectric energy harvesting system.

2. MATERIALS AND METHODS

This study is an extension of the result of an experimental study of [49]. In the design of foot beats piezoelectric energy generating setup, the selection of materials, working principle and model prototyping are required. Ibhaze et al. [40] have shown that the amount of energy to be converted, the working principle of piezoelectric sensors, and how the energy is to be generated are requisite in prototyping a possible solution in selection of the type of material to be used in the system. In this case, the piezoelectric generator is built to harvest electrical energy through pressure from the foot beats arising from the foot beats of dancers in dance club centres using piezoelectric sensors.

2.1 Materials

In this study, materials used include: 300 mm x 300 mm x 25 mm thick wooden board, 3 mm thick plywood of the same dimension, 150 mm x 150 mm electric unit box, human weight of different kilogrammes, electric panel, foam spring, Lead Zirconate Titanate (PZT) piezoelectric sensors, rectifiers (diodes), capacitors, resistors, 6V4AH Lead acid rechargeable battery, multimeter, AC nipple neutraliser, current controllers (switches), electric strand wire, LED and USB output.

2.2 The Working Principle and Experimental Setup

A sheet of plywood was placed above 12 piezoelectric sensors unit connected in series on a hard wooden board, because the power output from one piezo crystals were found to be very low. Between the plywood and hard board, a foam spring was placed at the corners. Then sensors were placed at the middle of board in 3 x 4 arrangement as shown in Fig. 1. This was connected to a box placed on a second board where the output can be indicated or appliances connected. Subsequently, the piezoelectric platform was prepared for stepping.

Usually, the voltage output from a single piezo-sensor was extremely low, therefore combination of 12 piezoelectric was used. Since the output of the piezoelectric material is not a regulated one, variable to linear voltage converter circuit rectifier was used. In this case, AC ripple neutralizer was the circuit used to reduce the ripples from the piezoelectric output. The AC ripple neutralizer consists of rectifier and ripple filter. AC ripples were filtered out using ripple filter and it was used to filter out any further variations in the output and then it can be pass through regulator in order to regulate, and it is constant until the load and mains voltage is kept constant.

Likewise, the output of the voltage regulator is given to the unidirectional current controller which allows flow of current in only one direction. In this system, diode was used as a unidirectional current controller which main function was to allow the flow of current in only one direction while blocking current in the reverse direction.

The piezoelectric sensors convert the pressure from the foot beats to electrical energy when pressed and store same in batteries that can be used in real time or at a later time to power the desired devices. A battery was connected to the system to store energy for future use. In this case, a LED display was shown using this foot power. The block diagram of footsteps electricity generation is shown in Fig. 2. The block diagram representation typical of a piezoelectric energy generating setup is shown in Fig. 2.

As the gadget was placed under the dancing floor, electricity was generated from the pressure from the foot beats of dancers. The electricity generated charged the battery which could be used to energise electrical appliances when the pressure was withdrawn. Multimeter was used to determine the amount of energy generated in the system as shown in Fig. 3. As varying pressure from the foot beats were applied on the piezo material, different voltage and current readings corresponding to the force was displayed. For each such voltage reading across the force sensor, various voltage and current readings of the piezo material are recorded. The whole process is demonstrated in Fig. 4.

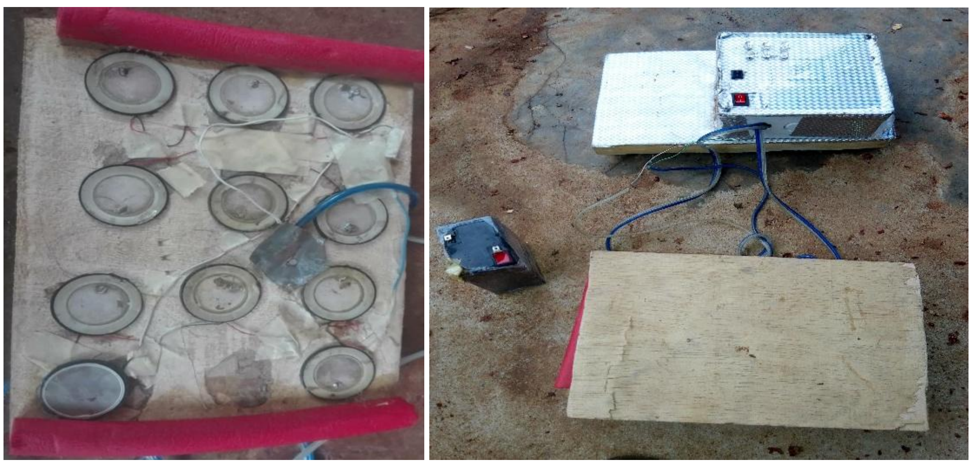

Fig. 1. The arrangement of piezo sensors and connections in the system

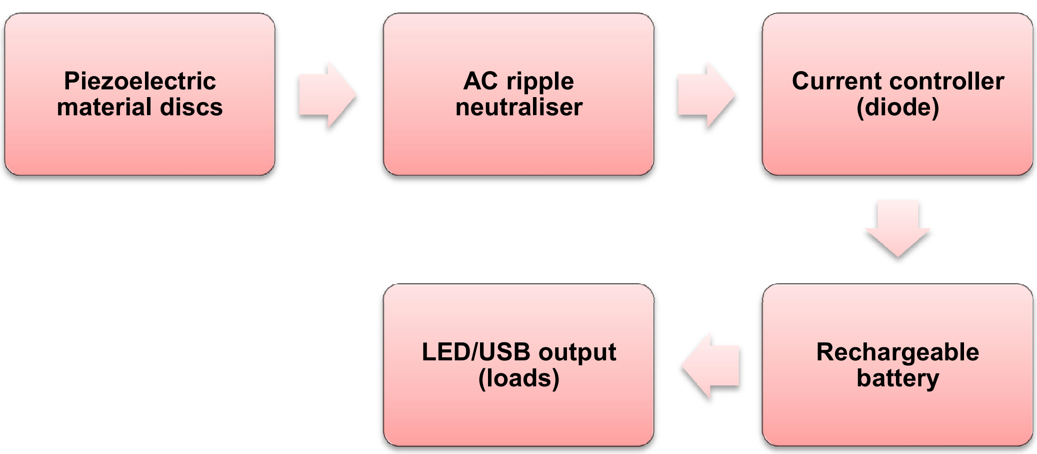

Fig. 2. Block diagram of footsteps electricity generation

Fig. 3. Multimeter connected to the system for reading of voltage and current

Fig. 4. Experimenting the system

The general theoretical equations for the electric outputs of a piezoelectric energy harvesting device (EHD) directly connected with an electric resistor are shown in Equations 1 and 2 as;

$$V_R(t) = I_R(t) \times R \quad (1)$$

$$P_R(t) = V_R(t) \times I_R(t) \quad (2)$$

Where,

V_R (t) = the voltage across the resistive load;

I_R (t) = the current through the resistive load; and

P_R (t) = the power dissipated in the resistive load, which is a good indication of the actual power generated by the piezoelectric EHD.

However, piezoelectric materials are known to generate voltage across their surface whenever they are subjected to mechanical stress and the generated voltage is stored in a capacitor such that the relationship between the stored charge and voltage is shown as in Equation 3;

$$Q = C \times V \quad (3)$$

Where,

Q = Charge measured in coulombs, C = Capacitance measured in Farads, V = Voltage across the capacitor measured in Volts. The energy produced by the piezoelectric sensors follows directly from Equation 3 and given as in Equation 4;

$$E = \tfrac{1}{2}Q \times V = \tfrac{1}{2}C \times V^2 \quad (4)$$

Where,

E = Energy measured in Joules.

In order to calculate the electric voltage generated from the deformation of the piezoelectric ceramic, it is necessary to know the constant of the piezoelectric correspondent to the material. This constant defines the ratio between the dimensional variation Δl of the piezoelectric material in meters and the potential difference applied in Volts. It defines the generation of electric loads in Coulombs and the force applied in the material in Newtons.

The voltage generated by mechanical load acting on a determined area of a piezoelectric Lead Zirconium Titanate (PZT) is defined by Equation 5.

$$V_g(t) = d_{33} \times \frac{f(t)}{C_p} \quad (5)$$

Where,

$f(t)$ = pressure, d_{33} = the piezoelectric strain constant, Cp = piezoelectric crystal equivalent capacitance.

But C_p is given as in Equation 6;

$$\mathrm{C_p} = \mathrm{k} \times \frac{\mathrm{A}}{\mathrm{h}} \quad (6)$$

Where,

k = dielectric constant.

After the polarisation of the piezoelectric crystal material, the piezoelectric sensors will produce deformation (i.e., when under pressure). Hence, the piezoelectric sensors on both sides of the conductive layer will produce charge and voltage. In this case, the piezoelectric sensors can be equivalent to a capacitor and a resistor in parallel; though the capacitance is very small but the parallel resistance value is very large. The pressure and the voltage generated by the piezoelectric crystal V(t) can be expressed as in Equation 7;

$$V_g(t) = \frac{f(t)}{A} \times \frac{h}{G_{33}} \quad (7)$$

Where,

$f(t)$ = pressure, A = Crystal surface area, h = Crystal thickness, G_{33}= Piezoelectric voltage constant, d_{33}= Piezoelectric strain constant, C_p= Piezoelectric crystal equivalent capacitance.

Since the weight of human body is fixed, every time the force, F is applied to the piezoelectric sensors, the generated voltage, V_g becomes

$$V_g = \mathrm{AG}_{33} \quad (8)$$

Therefore, energy produced by the piezoelectric sensors then becomes

$$E_g(\mathrm{t}) = \frac{1}{2}\mathrm{C_P} \times \mathrm{V_g^2} \quad (9)$$

The experimental results are presented and discussed in section 3.

3. RESULTS AND DISCUSSION

Table 1 presents the direct piezoelectric sensor readings when dancers of different average weights stepped on the experimental platform. As in this case, 12 piezo electric sensors (discs) were placed in one square foot of an experimental platform. The result showed that the piezo sensors readings vary when different weights of persons were stepped on them due to varying pressure. The gadget was placed under the dancing floor to determine the readings as the number of foot beats increases. Multimeter was connected across for measuring voltages and current. As varying forces were applied on the piezo material, different voltage readings corresponding to the force were displayed.

From Table 1, it showed that one foot beat of an average 50 kg, 60 kg and 80 kg dancers produced an average voltage of 0.555 mV, 0.668 mV and 0.838 mV respectively and current of 0.063 mA, 0.081 mA and 0.087 mA respectively. The power generation of piezo sensor varies with different beats which was as a result of the pressure of the foot beat and the weight of the dancer.

As the pressure due to foot beats increases, the corresponding voltage and current readings of the piezo sensors were recorded as presented in Tables 2 and 3.

Table 2 shows the result of the voltage produced when the weights of the dancers were varied with increase in the number of foot beats. It showed that greater amount of voltage is produced when the weight of a dancer is increased at the same number of foot beats. This implies that the battery will be fully charged with a lesser number of foot beat at an increased weight. This scenario is graphically represented in Fig. 5.

Table 1. Piezo sensor outputs

Piezo sensor	Voltage (mV)			Current (mA)		
	50 kg	60 kg	80 kg	50 kg	60 kg	80 kg
1	0.520	0.680	0.820	0.064	0.080	0.088
2	0.612	0.650	0.860	0.063	0.080	0.085
3	0.560	0.680	0.840	0.064	0.083	0.088
4	0.540	0.645	0.770	0.065	0.080	0.092
5	0.560	0.680	0.860	0.065	0.083	0.086
6	0.600	0.654	0.840	0.062	0.083	0.089
7	0.582	0.650	0.864	0,060	0,080	0,082
8	0.546	0.684	0. 804	0.062	0.080	0.088
9	0.522	0.684	0.866	0.061	0.082	0.090
10	0.510	0.645	0.850	0.062	0.080	0.086
11	0.558	0.680	0.842	0.065	0.083	0.090
12	0.552	0.680	0.840	0.061	0.083	0.083
Average	0.555	0.668	0.838	0.063	0.081	0.087

Fig. 5 shows that at the same number of foot beats, the amount of voltage produced is greater at an increased average weight of the dancers. This implies that people with greater body mass generate larger amount of voltage per foot beat due to the greater amount of pressure exerted on the piezo materials. For example, at 1000 number of foot beats, the amount of voltage generated by a 50 kg dancer was 555 mV, 668 mV for a 60 kg dancer and 841 mV for an 80 kg dancer respectively.

Table 3 shows the result of the current produced when the weights of the dancers were varied with increase in the number of foot beats. It showed that greater amount of current was produced when the average weights of dancer were increased at the same number of foot beats. This scenario is graphically represented in Fig. 6.

Fig. 6 shows that at the same number foot beat, the amount of current produced was greater at an increased weight of the dancers. This implies that people with more body mass always generate greater amount of current per foot beat due to the greater amount of pressure exerted on the piezo materials. For example, at 1000 number of foot beats, the amount of current generated by a 50 kg dancer was 63 milliampere, 81.5 milliampere for a 60 kg dancer and 88 milliampere for an 80 kg dancer respectively.

The result of Table 4 is a derivation from Tables 1, 2 and 3 based on Equation 2. Table 4 shows the result of the power generated when the weights of the dancers are varied with increase in the number of foot beats. It shows that greater amount of power is generated when the weights of a dancer are increased at the same number of foot beats. This scenario is graphically represented in Fig. 7.

Fig. 7 shows that at the same number foot beat, the amount of power generated is greater at an increased weight of dancers. This implies that people with bigger body mass always generate greater amount of power per foot beat due to the greater amount of pressure exerted on the piezo materials. For example, at 1000 number of foot beats, the amount of current generated by a 50 kg dancer was about 35 Watts, 54 Watts for a 60 kg dancer and 74 Watts for an 80 kg dancer respectively.

Generally, the three results implied that body mass (weight) of the dancers is a determining factor in the generation of electricity through the foot beats despite the number of foot beats or the amount of time. In addition, The graphs gave a positive gradient which shows that as the number of foot beats increases, the power generation increases and as the current increases, the voltage and power also increases thus obeying the Ohms law which states that electrical current (I) flowing in a circuit is proportional to the voltage (V) and inversely proportional to the resistance (R), i.e as the voltage increased, the current increased provided the resistance of the circuit remain constant as shown in Figs. 5, 6 and 7.

This study is in support of studies such as [34, 38-42,44]. The study shares specific view with Ibhaze et al. [40] who argued that the amount of energy generated directly depends on the applied pressure while the voltage and current maximisation follows directly from the series-parallel connection of the transducers. The result strongly shares the same view with Aman et al. [41], Rakhe and Singh [41] and Shiraz and Farrukh [43] who found that an increase in weight of a person while walking, running or dancing increases the amount of electricity generated through piezo electric crystals.

However, the increase in voltage in the battery is subject to the maximum voltage capacity of the battery. In this case, the voltage remains steady no matter the amount of applied force or pressure from the foot beat. It implies that at this point also, power and current generated in the system remain steady.

Table 2. Voltage charge (V) in battery from different average human weights per varying number of foot beats

No of foot beats	Voltage charge (mV) in battery		
	50 kg weight	60 kg weight	80 kg weight
100	55.5	66.8	84.1
200	111	133.6	168.2
300	166.5	200.4	252.3
400	222	267.2	336.4
500	277.5	334	420.5
600	333	400.8	504.6
700	388.5	467.6	588.7
800	444	534.4	672.8
900	499.5	601.2	756.9
1000	555	668	841

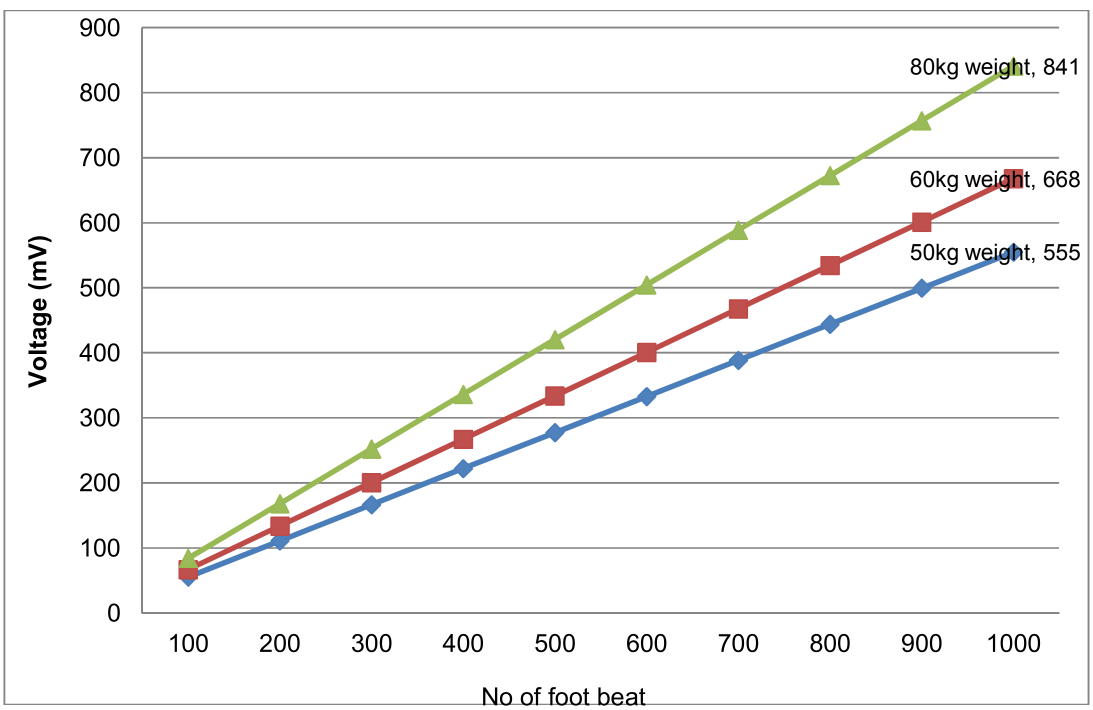

Fig. 5. Graphical comparison of voltage charge (V) in battery from different average human weights per varying number of foot beats

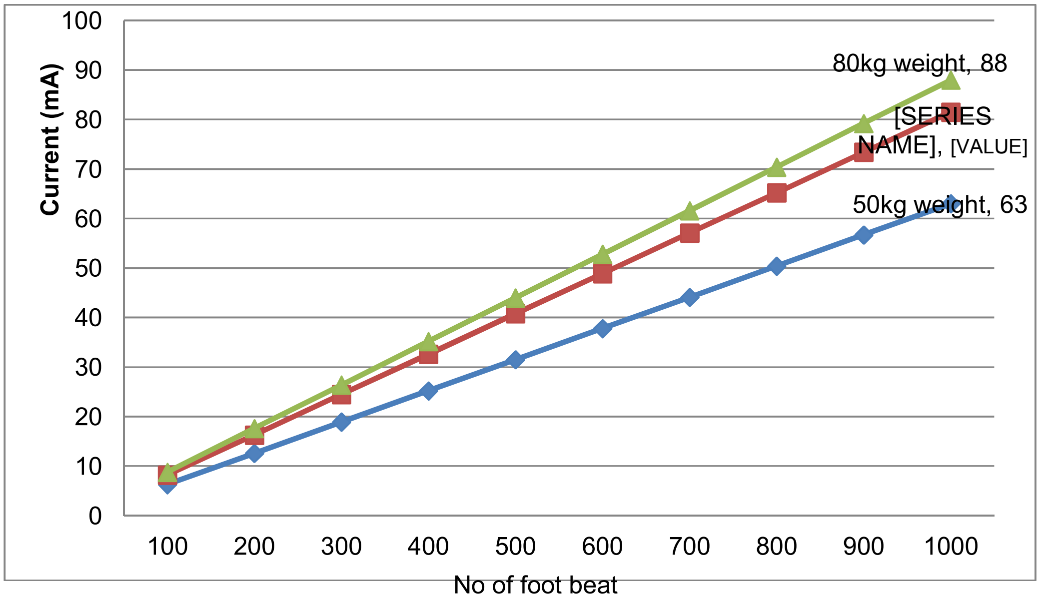

Fig. 6. Graphical comparison of current (V) in battery from different average human weights per varying number of foot beats

Table 3. Current (A) generated from different average human weights per varying number of foot beats

No of foot beats	Current (mA)		
	50 kg weight	60 kg weight	80 kg weight
100	6.30	8.20	8.80
200	12.60	16.30	17.60
300	18.90	24. 50	26. 40
400	25.20	32.60	35.20
500	31.50	40.80	44.00
600	37.80	48.90	52.80
700	44.10	57.10	61.60
800	50.40	65.20	70.40
900	56.70	73.40	79.20
1000	63.00	81.50	88.00

Table 4. Power (W) generated from different average human weights per varying number of foot beats

No of foot beats	Power (mW)		
	50 kg weight	60 kg weight	80 kg weight
100	349.65	544.42	740.08
200	1398.60	2177.68	2960.32
300	3146.85	4899.78	6660.32
400	5594.40	8710.72	11841.28
500	8741.25	13610.50	18502.00
600	12587.40	19599.12	26642.88
700	17132.85	26676.58	36263.92
800	22377.60	34842.88	47365.12
900	28321.65	44098.02	59946.48
1000	34965.00	54442.00	74008.00

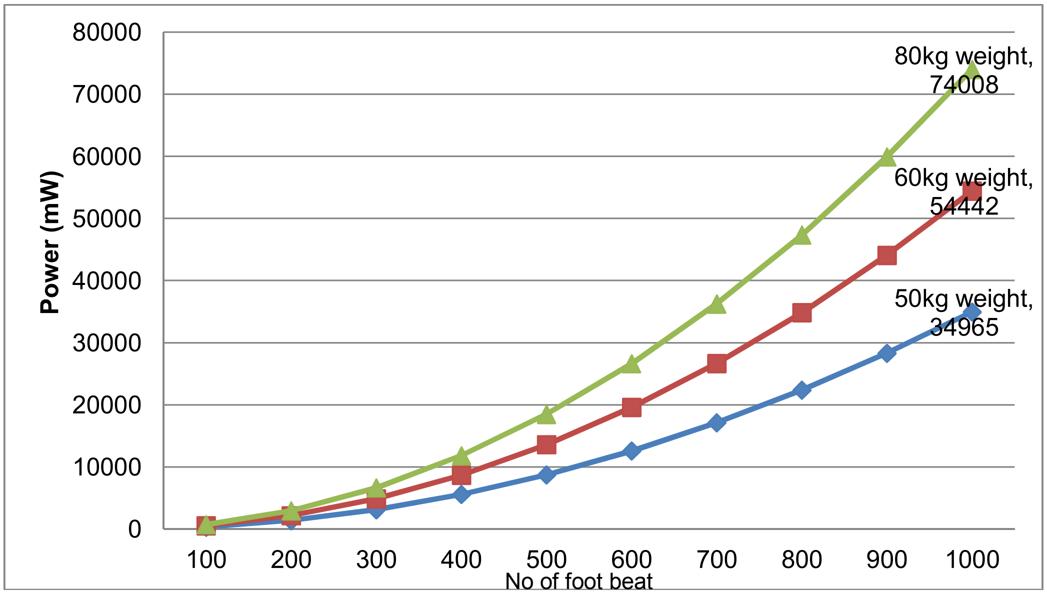

Fig. 7. Graphical comparison of power (W) in battery from different average human weights per varying number of foot beats

4. CONCLUSION

As effort toward meeting the electricity demands in Nigeria and at the same time minimising the adverse effect of fossil fuel electricity generation continues, this study demonstrated that energy from the weight of human body that is usually wasted through body movements and other human activities could be converted into a useful electrical energy and stored for future use using piezoelectric materials.

In this system, it is expected that the amount of voltage charge in the battery as well as power and current in the system would continue to increase as weight increases but to the maximum voltage capacity of the battery connected in the system. At full charge, the battery is expected to stop charging irrespective of the amount of applied pressure.

Expectedly, this system of electricity generation has the potential of alleviating the problem of electricity supply and meeting of Vision 2030 Sustainable Development Goals for electricity mix in Nigeria. In addition, it is environmentally, economically and socially sustainable; and capable of powering small electrical appliances and electronic gadgets such as cell phones, radio stereo, television, fan, and even powering street lights on the highways through a system whereby vehicles run on the laid piezoelectric materials on the road. But mostly required where there are high volumes of human traffic and places that consume minimal amount of electricity like club houses, markets, and worship centres, shopping malls, bus stations, parks, etc. The downside of this system however, is the amount of energy it generates which is usually very small and cannot be used in a large scale though can be optimised. To this end, there is need for more robust research in this area and increase genuine interest in alternative and sustainable energy research by the Nigerian government.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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