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DESIGN AND DEVELOP A PIEZOELECTRIC POWER GENERATOR AND ENERGY HARVESTER UTILIZING HUMAN FOOTSTEPS

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Abstract: The development of sustainable energy technologies has encouraged the exploration of alternative methods for converting mechanical energy into electrical energy. One promising approach is piezoelectric energy harvesting, which utilizes the pressure generated by human footsteps to produce electrical output. This research aimed to design and developed a piezoelectric power generator prototype and evaluate its voltage output under different human-weight conditions. An experimental research design was employed, involving five participants with body weights ranging from 56 kg to 62 kg. Each participant performed footstep pressure tests on the prototype at a consistent walking pace, with voltage measurements recorded using a digital multimeter across three one-minute trials. The results showed an increasing trend in voltage output as participant weight increased, with average outputs ranging from 10.2 V at 56 kg to 16.3 V at 62 kg. Linear regression analysis revealed a strong positive relationship between participant weight and voltage output, with a coefficient of determination (R^2) of 0.9815. The resulting regression equation was $y = 0.9991x – 45.368$. These findings demonstrate the potential of the developed prototype to generate electrical voltage from human footsteps. Further improvements in material selection, circuit design, energy storage, and prototype durability are recommended to enhance its performance and practical application in sustainable energy systems.

Keywords: *energy harvesting, human footsteps, piezoelectric power generator, weight–voltage correlation, sustainable energy solutions, mechanical energy conversion*

INTRODUCTION

The pressing issues of climate change and the limited availability of non-renewable energy resources have created a growing need for sustainable energy alternatives (Lv, 2023). As the world transforms into an interconnected global community driven by escalating energy demands, Earth's resources remain finite, necessitating a robust response to climate change and a decisive shift towards renewable energy sources (Bashiru et al., 2024). This transition is crucial for meeting future energy needs while addressing human development, well-being, and health concerns. Interestingly, while global energy production is growing rapidly, renewable energy technologies, such as wind, biomass, hydropower, geothermal, and solar, are reaching maturity (Sagir & Bahadır, 2003). However, the adoption of these technologies faces challenges, including market failures, limited access to information, the need for essential raw materials, and rising carbon emissions (Bashiru et al., 2024). Additionally, the coupling of economic growth with energy use has created pressure on the supply of energy resources, further emphasizing the need for sustainable cleaner production and sustainable energy options (Sáez-Martínez et al., 2016).

Piezoelectric materials possess the unique ability to convert mechanical stress or vibrations into electrical energy, a phenomenon known as the piezoelectric effect (Howells, 2009; Hu et al., 2022). This property makes them highly valuable for energy harvesting applications, particularly in wearable devices and systems that capture ambient mechanical energy (Hu et al., 2022; Tian et al., 2018). The conversion of mechanical energy into electrical energy in piezoelectric materials occurs through the displacement of electrical charges within the crystal structure of the material when it is subjected to mechanical stress (Howells, 2009; Kabakov et al., 2023). This process can be

reversed, allowing piezoelectric materials to convert electrical energy into mechanical motion, making them versatile for various applications (Kabakov et al., 2023). Although piezoelectric materials offer significant potential for energy harvesting, they have certain limitations. There is often a trade-off between the piezoelectric strain and voltage constant, as well as between the piezoelectric performance and mechanical softness (Hu et al., 2022). However, recent advancements, such as the molecular bond weakening strategy in organic-inorganic hybrid piezoelectrics, have shown promise in mitigating these issues and improving overall performance (Hu et al., 2022)

Human footsteps are a significant renewable energy source with strong harvesting potential. Piezoelectric energy harvesting captures otherwise wasted mechanical vibrations from human activities (Sharma et al., 2022). As the population and infrastructure grow, footstep loads can provide substantial freely available energy (Sharma et al., 2022). Various mechanisms have been developed to capture it. Piezoelectric energy harvesting (PEH) tiles harness footstep energy with minimal interference during regular activities (Sharma et al., 2022). Unimorph PZT piezoelectric cantilevers convert kinetic energy from footsteps into usable electricity, with a conversion efficiency of 17.12 %(Panthongsy et al., 2018). Although the output from individual footsteps is small, cumulative generation may be significant. One study reported an average power of 1.24 mW and a total output energy of 3.49 mJ from a single footstep (Panthongsy et al., 2018). Another design generated 27.5 mW at 1.5 Hz, representing fast walking (Xie & Cai, 2014). These findings demonstrate the potential of human gait energy harvesting to power low-rated wearable electronic and medical devices (Gupta et al. 2023). Continued advances in design, materials, and efficiency should enhance the viability of footstep energy harvesting.

Developing methods to capture and utilize energy from human activities presents challenges because of the low frequency of human motion and the need for compact, flexible, and biocompatible devices. Human motion energy is concentrated in the low-frequency range (below 5 Hz), making it difficult to capture using traditional approaches (Pan et al., 2024). This necessitates designs such as the tumbler-inspired electromagnetic energy harvester (T-EMH) described by Pan et al. (2024), which converts irregular human motion into electricity. Piezoelectric materials have been explored to harvest energy from activities such as pressure, bending, and stretching (Park et al., 2012). Although outdoor renewable energy sources can provide power, they are unsuitable for electronics in indoor environments or implantable biomedical devices (Huang et al., 2019; Park et al., 2012). This highlights the need for approaches that supplement traditional power sources. Researchers are developing miniaturized, biodegradable power systems that harvest energy from the human body using biofuel cells, piezoelectric harvesters, triboelectric devices, and thermoelectric devices (Huang et al., 2019). This study aimed to design, develop, and evaluate a piezoelectric power generator prototype that converts mechanical energy from footsteps into electrical energy and investigate its feasibility, efficiency, and performance under various conditions.

STATEMENT OF THE PROBLEM

This study aimed to design and develop a piezoelectric power generator and energy harvester utilizing human footsteps. Specifically, it sought to evaluate the electrical output of the prototype under different human-weight conditions and determine the relationship between participant weight and voltage generation. Specifically, this study sought to answer the following questions:

1. What are the design features and components of the developed piezoelectric power generator prototype?
2. What is the voltage output generated by the prototype at different participant weights (56 kg, 57 kg, 59 kg, 60 kg, and 62 kg) across three experimental trials?
3. What are the mean voltage output and standard deviation obtained from the three experimental trials for each participant's weight?
4. Is there a significant linear relationship between the participant weight and the voltage output generated by the piezoelectric power generator prototype?
5. What regression model can be established to predict the voltage output based on the participant's weight?

METHODOLOGY

Method and Method Design

This study employed an experimental research method and conducted a controlled experiment to evaluate the performance of a piezoelectric tile power generator under various human-weight conditions. The energy harvested from the footstep pressure was measured using a digital multimeter. The results were compared with the control conditions or existing findings on energy-harvesting methods. Quantitative research quantified and collected the electrical energy output voltage (v) of the

prototype under different weight conditions in kilograms (kg). Statistical analysis was used to interpret the results and draw conclusions regarding the effectiveness of the prototype for energy harvesting. This approach enables a rigorous examination of the design and development of piezoelectric tile power generators.

Materials and Components

The materials and components listed in Table 3 for the assembly of the prototype piezoelectric power generator, along with the details of Table 4 for PZT (lead zirconate titanate) piezoelectric ceramic specifications.

Raw Materials for Piezoelectric Power Generator Prototype

No.	Description	Quantity
1	Ceramic Tiles 25x10x1cm	2 pcs.
2	Acrylic 25x1x1cm	1pc.
3	Light Emitting Diode (LED) Red	6pcs.
4	Rubber Foam 25x10x0.8cm	2pcs.
5	Spring 1"	2pcs.
6	PZT Piezoelectric Ceramics	20pcs.
7	Plywood 25x21x1.5cm	1pc.

PZT Piezoelectric Ceramics Specifications



Product Name: FT-27T-3.9A1LC 27mm Piezo Element with Wire 3.9 khz

Product Specifications	
Thickness: 3.36mm	Sound Pressure Level: 85DB 10cm
Diameter: 35mm	Rated Voltage: 1.8v
Material: Nylon	The input voltage: 30vp-p max
Output Type: Analog	Operating Temperature: -20 ~ 70 °C
Input Type: AC, DC	Storage Temperature: -30 to 80 °C
Resonant Frequency: 10+/-0.5KHz	Duration: Repeating every 1.2 sec
Resonant Impedance: 100RMAX	Static Capacitance: 8000pf +/- 30%

Prototype Design

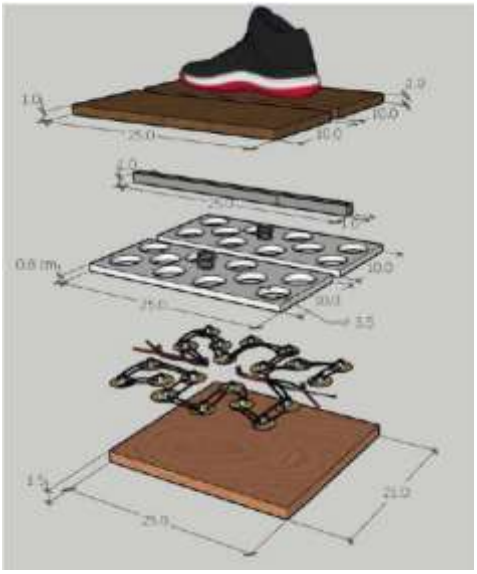


Fig. 1 Piezoelectric Power Generator Prototype Layout
Note: measurement is in Centimeters

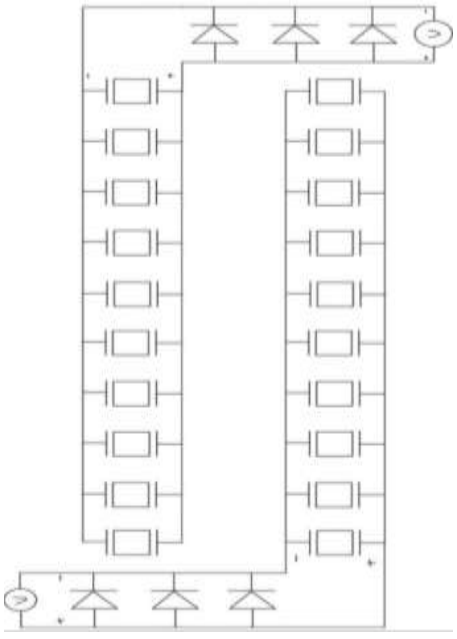


Fig. 2 Piezoelectric Power Generator Schematic Diagram

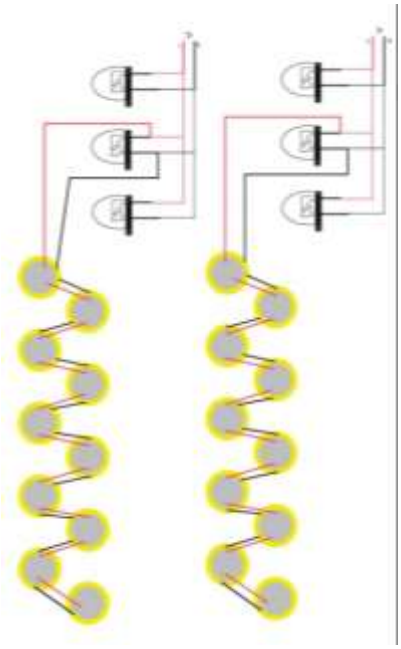


Fig. 3 Piezoelectric Power Generator Circuit Diagram

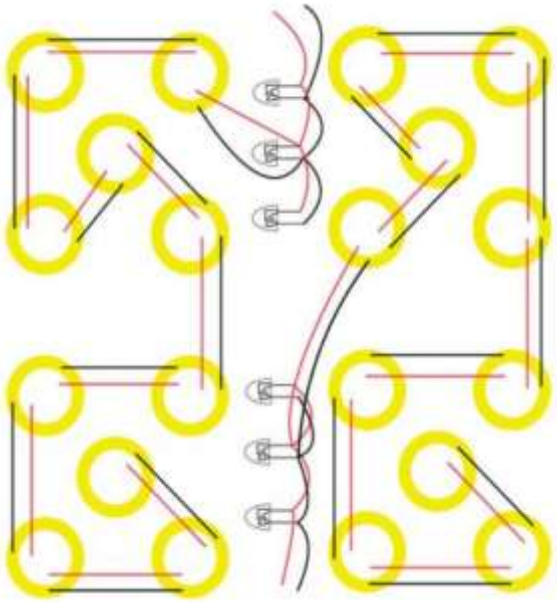


Fig. 4 Piezoelectric Power Generator Wiring Diagram

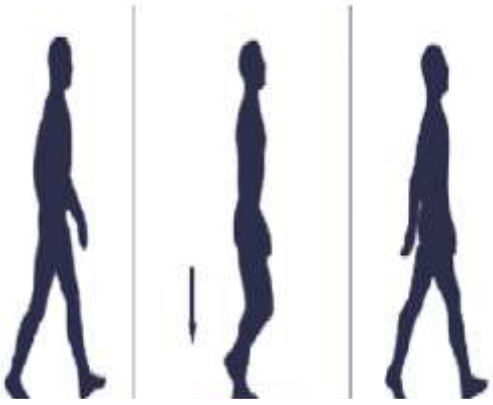


Fig. 5 Piezoelectric Power Generator Circuit Diagram

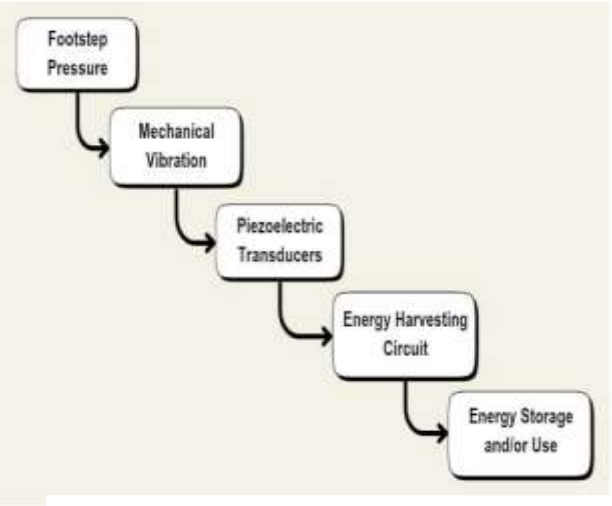


Fig. 6 Piezoelectric Power Generator Block Diagram

Experiment Setup

The experimental setup of this study investigated the relationship between the participant weight and voltage output from a piezoelectric power generator. The dependent variable was the participant weight, and the independent variable was the voltage output. Data collection was controlled at one-minute intervals per set, with three sets for thorough analysis. Each set involved recording the participant weight, measuring the voltage output at one-minute intervals, and maintaining controlled conditions. This approach aims to provide insights into the efficiency of piezoelectric power generators for harvesting energy from human footsteps based on varying weights and voltage outputs.

Data Collection Procedure

The detailed procedures for data collection included specifying the number of participants, type of data collected in voltage, duration of data collection sessions, and explanation of how the data would

be recorded and stored. This structured approach to data collection will enable a comprehensive evaluation of the efficiency and effectiveness of the piezoelectric power generator in harvesting energy from human footsteps, with participant weight as a key variable influencing the voltage output

Measurement and Analysis

Descriptive statistics, such as the mean, standard deviation, and range, were used to summarize the data collected during the energy-harvesting process. Inferential statistics, specifically linear regression analysis, were used to model the relationship between the input parameters and power output, helping to predict power generation under conditions

RESULTS

Experimental Setup Results

The experimental setup was designed to test the efficacy of piezoelectric power generators in real-world conditions. The piezoelectric power generator prototype was connected to a digital multimeter to monitor the output voltage generated by the mechanical stress caused by footsteps. The experiment was conducted under three conditions: same walking speed, participant weight, and planar pressure of the foot. The weights of the participants were 56, 57, 59, 60, and 62 kg, and the footstep pressure was applied using a piezoelectric power generator prototype under controlled conditions. To simulate a pressure pattern, each participant was instructed to apply footstep pressure over the prototype for one minute at a consistent pace equivalent to the normal walking speed. This process ensured that the pressure exerted on the piezoelectric material closely resembled the typical forces generated during human walking. Finally, the output from the piezoelectric device was recorded after each one-minute walking session.

Output Voltage of the Prototype

This study thoroughly examined the electrical output of a piezoelectric power generator prototype activated by varying the weights of pedestrians that produce ambient energy, that is, footstep pressure. This demonstrates the ability of the prototype to effectively convert mechanical energy from footfall pressure into usable electrical energy. Experiments were conducted to measure the output voltage generated by piezoelectric materials in response to the human footsteps. Participants from different weight classes applied pressure at one-minute intervals, providing a range of mechanical stress to the power generator prototype.

Table 1 Results of the Footsteps Pressure in the Prototype - Raw

Weight (kg)	**Voltage Output (v)**		
	Set 1	**Set 2**	**Set 3**
56	10.1	10.4	10.2
57	11.7	12.3	11.8
59	13.2	13.8	13.8
60	13.7	15.6	15.4
62	16.1	16.2	16.5

Note: Actual Voltage Output within one-minute Footstep tapping

For the participant weighing 56 kg, consistent voltage production was observed, with recorded outputs of 10.1V, 10.4V, and 10.2V. Marginally heavier, the 57 kg individual displayed a slight uptick in voltage generation, with values of 11.7V, 12.3V, and 11.8V. By advancing the participant to a mass of 59 kg, the voltage output showed a further increase, with values of 13.2V, 13.8, and 13.8V. The highest output was produced by the participant weighing 60 kg, who elicited voltages of 13.7V, 15.6V, and 16.5 V. The results establish a positive correlation between the weight 62 kg, who pedestrians and the voltage output of 16.1V, 16.2V, and 16.5V. The results establish a positive correlation between the weight of pedestrians and the voltage output of the piezoelectric generator.

These findings suggest a substantial relationship between the mass exerted on the piezoelectric material and the resultant electrical output. This indicates the significant influence of pedestrian weight

on the voltage generation capability of the piezoelectric prototype, and that the increased mechanical stress emanating from heavier footfalls directly affects the magnitude of the electrical output. Understanding the relationship between piezoelectric materials and energy harvesting is crucial. Experiments on the piezoelectric prototype showed a direct connection between pedestrian weight and voltage output, indicating the potential use of human footsteps as an energy source for power generation applications.

Table 2 Results of the Footsteps in the Prototype – Treated

No.	Weight (kg)	Voltage (v)			
		Set 1	Set 2	Set 3	Average
1	56	10.1	10.4	10.2	10.2
2	57	11.7	12.3	11.8	11.9
3	59	13.2	13.8	13.8	13.6
4	60	13.7	15.6	15.4	14.9
5	62	16.1	16.2	16.5	16.3
$\bar{x}$	58.8	13.0	13.7	13.5	13.4
σ	2.4	2.2	2.4	2.6	2.4

Note: Data are Statistically Treated: Average, Mean, and Standard Deviation

Table 2 and Figure 7 show that the data suggest a positive correlation between the weight and voltage output, indicating that higher weights generate higher voltages. This trend is consistent across all sets and is reflected in the increasing average voltage.

This demonstrates that the prototype generates higher voltage outputs with increasing weight, showing a positive correlation. The voltage outputs were consistent, particularly at lower weights, with some variability observed for the person weighing 60 kg. These results suggest that the piezoelectric power generator prototype effectively converts the mechanical energy of the footsteps into electrical energy with better performance at higher weights. This implies that the prototype is more suitable for use by individuals in higher-weight brackets for optimal energy generation.

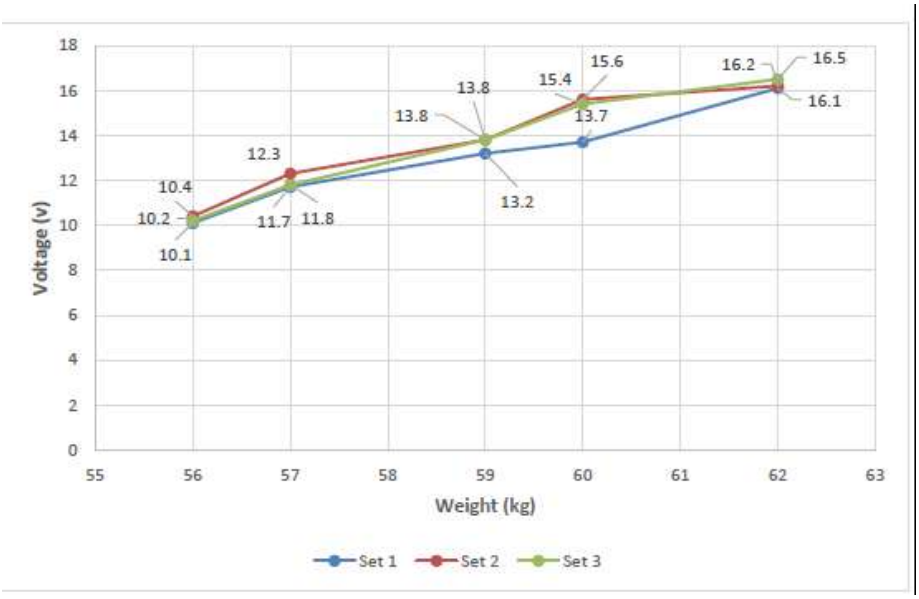


Figure 7 Weight and Voltage Output per Set Comparison The use of Simple Linear Regression Analysis on the experimental data has provided valuable statistics that demonstrate the reliability and effectiveness of this prototype. The coefficient of determination, $r^2 = 0.9815$, 98.15% of the variability in the observed voltage output is explained by changes in applied weight, highlighting the strong

predictability and relationship. Concurrently, the coefficient of correlation, r = 0.9907, further strengthens this strong positive linear relationship. Exploring the slope's 95% confidence interval shows bounds between 0.75 and 1.25, indicating a strong level of certainty on the gradient of the linear model and confirming the consistent impact of weight on voltage generation. The standard error of the slope, $_s(b_1)$ = 0.0791, ensures that the estimated regression line aligns closely with the true slope. The accuracy of the voltage output prediction without an applied weight is also remarkable, as indicated by the 95% confidence interval for the intercept (-60.179858 to -30.556142) and its low standard error of 4.65424. The ANOVA results support the model, with a high $F_{statistic}$ = 159.539 and a very low P_{value} = 0.0011 results, leading to the rejection of null hypothesis, H_0, and confirmation of the significance of the regression.

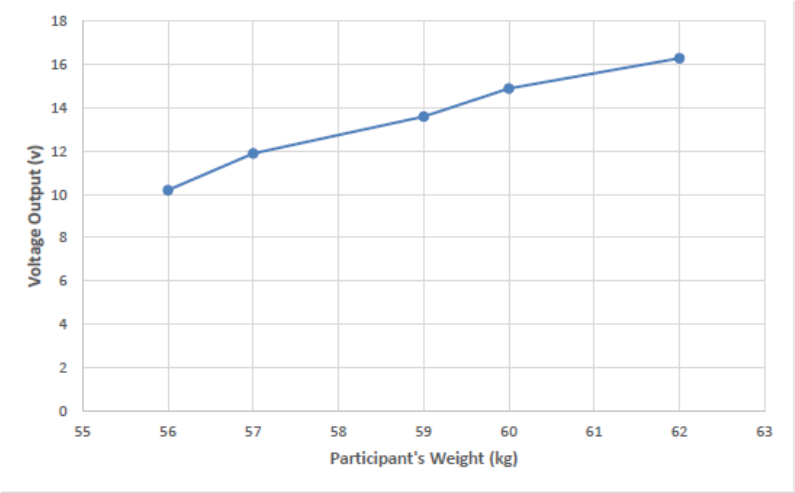


Figure 8. Weight and Average Voltage Output Relationship

Finally, the researcher expresses that regression equation, $y = 0.9991x - 45.368$, serves as a predictive tool in offering quantifiable insight into the relationship between applied weight and subsequent voltage output. With each incremental weight unit, the voltage output was anticipated to increase by 0.9991 units, indicating a near-perfect proportional relationship. The -45.368 y-intercept value theoretically represents the baseline voltage in the absence of weight and addresses the inherent electrical offset of the energy-harvesting system.

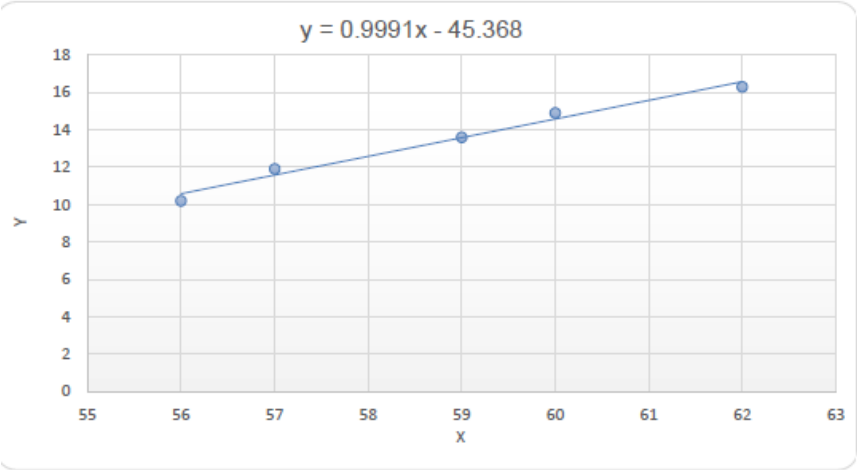


Figure 9. Regression Equation of Weight and Voltage

The analysis shown in Figure 22 provides an accurate model that validates the piezoelectric power generator prototype and demonstrates the potential scalability and application of such technologies for future energy generation solutions. The results of the simple linear regression analysis of the experimental data confirmed a strong positive linear relationship between the applied weight and voltage output in the prototype power generator.

Efficiency of Energy Harvesting

The efficiency of an energy-harvesting system indicates its capacity to convert mechanical energy into electrical energy. Hence, assessing the efficiency of the piezoelectric power generator prototype used in this study is crucial for understanding its practical application. To calculate the efficiency of the prototype, the ratio of the electrical energy output to the mechanical energy input was determined.

In terms of theoretical predictions, an intrinsic conversion efficiency can be anticipated based on the piezoelectric material constants and the mechanical–electrical energy conversion process involved. However, the actual efficiency of the prototype may exhibit discrepancies when juxtaposed with the empirical results from experimental data. These discrepancies can arise because of several extrinsic and intrinsic factors that affect the energy conversion.

The type of piezoelectric material used was an intrinsic factor. The energy conversion efficiency of piezoelectric materials, such as polyvinylidene fluoride, can vary owing to their piezoelectric coefficients and flexibility (Piezoelectric, 2023). within the prototype, and their interactions with the mechanical structure are crucial. Flat plates, curved, cantilever, and extensional structures serve as various configurations that determine the process of capturing mechanical energy and converting it into electrical energy (Zhao et al., 2023).

Mechanical design encompasses factors such as the placement and integration of piezoelectric elements within the prototype, which can affect the stress distribution and, therefore, the efficacy of energy conversion (He et al., 2020). The energy delivered to external resistive loads or electrical circuits should match the impedance for an optimal power transfer (Zhao et al., 2023).

When discussing the factors affecting efficiency, it is crucial to recognize that an improvement in one aspect may necessitate compromises in the other. For instance, while certain piezoelectric materials may offer greater energy conversion efficiency, they may also encounter limitations in terms of durability or power output (Zhao et al., 2023). Similarly, a mechanical design that maximizes energy capture from human walking may not be the most feasible or practical for everyday use (Behrendt et al., 2023).

Optimizing a piezoelectric energy-harvesting system involves balancing theoretical expectations with practical functionality and considering the material properties, system configuration, and mechanical design to enhance the overall efficiency. In addition, the configuration of the piezoelectric elements contributes to the overall efficiency. For instance, the geometry and placement of the piezoelectric elements

Energy Storage and Utilization

In a groundbreaking study examining a prototype piezoelectric power generator for energy harvesting through human footsteps, attention was paid to how energy is stored and used. This study focuses on the accumulation and maintenance of energy, particularly in modern energy-storage solutions, such as capacitors and batteries. The collected substantive data portraying the effectiveness of the harvested energy can be sequestered within these storage units, reflecting the potential of the prototype in real-world applications (Energy storage, 2023).

The performance metrics of the energy storage system were carefully analyzed, focusing on the charge and discharge cycles of the capacitors or batteries used. These cycles indicate the durability and operational sustainability of the device, which are crucial for evaluating energy-harvesting technologies (He et al., 2020). The ability of a storage system to maintain and release stored energy without significant losses is essential for assessing the overall effectiveness and long-term suitability of a prototype. The harvested energy was demonstrated through practical applications, such as self-powered LED lights and small-scale electronic gadgets. A piezoelectric power generator prototype successfully powered these devices, demonstrating the versatility and utility of the energy source (Wu et al., 2021). For example, research has documented the illumination of LED lights using energy from piezoelectric materials, demonstrating their tangible contribution to technological advancement and sustainability. This study laid a critical foundation for developing innovative green energy solutions that can power various devices, potentially leading to a shift towards renewable energy sources in industrial and

consumer domains (Green Technology News, 2023).

DISCUSSION

The experimental results from the piezoelectric power generator prototype offer a comprehensive interpretation, with the data revealing a clear correlation between the weight of the participants and voltage output generated by the prototype. The voltage output increased noticeably as the pedestrian weight increased, supporting the basic piezoelectric principle that larger forces on these materials produce greater electric charges (Piezoelectricity, 2022). This principle aligns with the foundational work of Jacques and Pierre Curie, who discovered the piezoelectric effect in 1880, wherein certain materials produce electric charges under mechanical stress (Zhao et al., 2023).

These data support previous claims regarding the performance of piezoelectric materials. For example, an increase in the voltage output with weight signals indicates that the transduction efficiency of the prototype adheres to the expected piezoelectric behavior of polarized materials under stress (Zhao et al., 2023). This adds to the existing body of knowledge by providing a quantitative demonstration of these theoretical predictions in an innovative application, power generation through human footsteps. The results should also consider the observed plateau in the voltage increase. This indicates that a threshold of mechanical stress might be causing a less pronounced increment in voltage production for the piezoelectric materials used. This has prompted additional investigations into the material properties and limitations that mediate the efficacy of energy harvesting (Zhao et al., 2023).

The results validate and build upon prior studies, confirming the viability of piezoelectric generators in practical applications, such as low-power consumption devices. However, certain deviations from the theoretical models indicate a complex interplay of factors in real-world applications that could influence the direct implementation of these materials in urban planning or consumer products. These findings help bridge the gap between theoretical models and practical applications, making a noteworthy contribution to the field of piezoelectric energy harvesting and opening avenues for future refinements in material science and engineering design (Wu et al., 2021).

Implications for Design and Development

The investigation and subsequent results surrounding the piezoelectric power generator prototype have profound implications for the design and future development of piezoelectric energy harvesting devices (Wu et al., 2021). The experimental data endorse the correlation between participant weight and voltage output, a finding that reinforces not only the fundamental principles of piezoelectricity but also aids in refining the design strategies of piezoelectric generators. The increase in electrical output with a higher mechanical force offers important insights into the design of these systems. Maximizing energy conversion may depend on optimizing the materials and structures to handle stress levels during human movement (He et al., 2020).

Considering the experimental observations, it is imperative to consider design adaptations that can capitalize on the range of mechanical energies presented by different users. For instance, the incorporation of materials with higher piezoelectric coefficients can potentially enhance the energy conversion rates. Additionally, the variable voltage outputs observed across different weights underscore the need for adaptable circuitry that can effectively handle these fluctuations in energy production (Fei et al., 2022). Acknowledging a plateau in the voltage output at certain stress thresholds requires a detailed analysis of the material properties, leading to potential improvements in the piezoelectric elements themselves or in the way they are integrated within the prototype. Durable materials that maintain their piezoelectric properties under repetitive loading could extend the lifespan and performance consistency of these generators (Fei et al.,2022). Based on these findings, recommendations for improving piezoelectric power generators include exploring alternative materials with strong energy conversion capabilities, optimizing mechanical configurations to better distribute and convert walking forces, and creating electronic interfaces that can be adjusted to variable power outputs. Implementing these improvements can enhance the efficiency and usability of piezoelectric generators and drive innovation for wider applications in wearable technology and smart urban infrastructure.

Comparison with Other Research

In the field of piezoelectric energy harvesting, comparing existing studies is important for assessing progress and identifying areas for improvement. According to a study by Yusran et al. (2020), research on a prototype piezoelectric generator revealed a direct relationship between the load mass and output

voltage, demonstrating its potential for converting mechanical pressure into electrical energy. The prototype achieved a substantial output, generating 10.4 volts under a 60 kg human load. The regression equation supports the effectiveness of the generator at high loads and its ability to generate electrical energy from mechanical energy. This study consolidates the existing literature on piezoelectric generators and highlights their potential for real-world applications in military missions and healthcare (Zhao et al. 2023).

However, piezoelectric energy harvesters, particularly those assimilated within the fabric of pedestrian activity, offer an attractive energy source owing to their inherent ubiquity and consistency, which are advantageous over the variable nature of solar and wind energy availability (Ghazanfarian & Mohammadi, 2021). Solar panels and wind turbines require vast expanses and optimal conditions, whereas piezoelectric harvesters capitalize on the relentless kinetic parade of human footsteps, converting motion into energy with a minimal spatial footprint or concern for weather patterns (Duque and Murillo, 2023). However, the efficiency of piezoelectric materials in converting mechanical to electrical energy, though promising, often do not rival the large-scale energy-generation capabilities of their solar and wind counterparts. The energy harvested from piezoelectric materials, which is beneficial for low-power applications, encounters a threshold that restricts its scope to meet higher energy demands without substantial scaling (Behrendt et al., 2023).

The use of piezoelectric materials to harvest energy from human activities offers several advantages. Their small size, flexibility, and ability to be integrated into different environments make them practical for capturing energy from daily movements. This decentralized approach reduces power transmission losses and allows for on-the-spot power generation. Additionally, ongoing materials science developments are expected to result in more efficient and long-lasting piezoelectric materials suitable for these applications (Wu et al., 2021). However, the disadvantages include the fragility of the piezoelectric components, which can sometimes be brittle, and a limited power output, which may not suffice for high-energy-consuming devices without extensive material usage. Moreover, although the conversion efficiency of solar technologies has improved notably over time, piezoelectric materials can be improved to develop energy density and durability under cyclic loading conditions (Behrendt et al., 2023). Compared with traditional methods, such as solar and wind energy, piezoelectric energy harvesters offer unique advantages for microscale power generation in urban settings. Despite their current limitations in efficiency and power output, they provide a supplementary energy source that can be harvested from the abundant available resources of human movement, a complementary stride towards sustainable energy diversification.

Practical Applications and Real-World Impact

The piezoelectric power generator prototype has shown great potential for real-world applications, particularly in the field of sustainable energy. It can be integrated into urban infrastructure, such as floor tiles in high-traffic pedestrian zones or within staircases, to generate electricity through human movement (Voleti et al., 2021). The technology also has the potential to be incorporated into wearable devices, providing additional power sources and reducing the dependency on traditional charging methods.

This embodied energy technique aligns seamlessly with global renewable energy goals, presenting an off-grid solution that contributes to reducing the carbon footprint associated with energy production and consumption (Smart Villages, 2022). The piezoelectric prototype epitomizes a closed-loop system, whereby energy efficiency is maximized by localizing energy generation to points of use, thereby diminishing transmission losses and curbing the environmental impact associated with energy transport (Sustainable Energy, 2023).

The commercial development and implementation of piezoelectric energy harvesting technologies are feasible and economically attractive. Markets for smart flooring solutions and interactive installations that leverage footfall energy conversion could burgeon, paving the way for pioneering start-ups and established companies. Furthermore, with the proclivity towards IoT devices and smart cities, the potential of piezoelectric generators to contribute to sensor networks, lighting systems, and other low-power applications is immense (Zhou et al., 2023).

Piezoelectric power generators play a significant role in the renewable energy sector by mitigating environmental impacts and utilizing previously untapped energy sources (Wu et al. 2021). Their commercial potential relies on ongoing material innovation and design optimization to enhance their effectiveness and longevity. With their strategic implementation, piezoelectric energy harvesting can become a key component of future sustainable energy solutions that align with human activity patterns

(Voleti et al. 2021).

CONCLUSION

This study presents a promising prototype of a piezoelectric power generator capable of harvesting energy from human footfalls. The experimental results demonstrated a strong positive correlation between participant weight and voltage output, with 98.15% of the voltage variability explained by the weight change. The regression equation $y = 0.9991x–45.368$ provides a predictive model for the voltage output based on the applied weight. Although the prototype shows potential for efficient energy harvesting from footsteps, challenges remain regarding its scalability and practical implementation. Nevertheless, this study provides valuable insights into piezoelectric energy harvesting and its potential applications in sustainable urban infrastructure and wearable devices. Further development and optimization of this technology could play a significant role in advancing renewable energy solutions and reducing carbon footprints.

RECOMMENDATIONS

Based on these conclusions, the following recommendations are made: Further research and development should optimize the piezoelectric power generator prototype by improving energy conversion efficiency and scalability through new materials or refined designs that capture more energy from footsteps. Larger-scale trials in pedestrian areas should assess performance and durability under varied conditions and prolonged use. Integration into sidewalks, staircases, or high-traffic flooring should be investigated to maximize energy harvesting. Applications in wearable devices and low-power electronics should be explored. Collaboration with urban planners and sustainability experts should support smart-city implementation strategies. Cost-benefit analyses should determine the economic viability of large-scale implementation and identify markets that could benefit most. Research on energy storage solutions is required to capture and distribute harvested energy for practical use. Safety and durability concerns must be addressed, and standardized testing and performance metrics should be developed to facilitate comparisons and advances in this field.

LIMITATIONS OF THE STUDY

This study was limited to testing a piezoelectric power generator prototype using five participants with different body weights ranging from 56 kg to 62 kg. The experiment was conducted under controlled conditions using a consistent walking speed and one-minute testing intervals. This study primarily focused on the relationship between participant weight and voltage output. However, the long-term durability, large-scale application, and actual energy conversion efficiency of the prototype have not been fully evaluated. Therefore, the findings may be limited to the specific prototypes and experimental conditions employed in this study.

FUTURE RESEARCH DIRECTIONS

Future studies should conduct experiments involving a larger number of participants and different walking conditions to further evaluate the performance of the prototype. They may also explore improved piezoelectric materials, circuit designs, and more efficient energy storage systems. Further testing in real-world environments, such as sidewalks, staircases, and high-traffic areas, is recommended to determine durability, scalability, and practical applications. Future studies should investigate the potential use of these devices in wearable and other low-power electronic applications.

ETHICS STATEMENT

This study involved the experimental testing of a piezoelectric power generator using human footsteps. The experiment focused on measuring the voltage output under different participant weight conditions. Appropriate care should be observed during the testing process to ensure participant safety, privacy, and confidentiality. The collected data were used solely for research purposes.

REFERENCES

Behrendt, C., Zhao, T., & Feng, Y. (2023). *Optimizing piezoelectric energy harvesting: Balancing efficiency, durability, and practicality*. *Mechanical Systems and Signal Processing*, 194, 111354. https://doi.org/10.1016/j.ymssp.2023.111354

Behrendt, J., Müller, K., & Fuchs, T. (2023). *Advances and limitations in piezoelectric energy harvesting: Applications and scalability challenges*. *Energy Harvesting & Systems*, 10(3), 215-233. https://doi.org/10.1515/ehs-2023-0032

Carter, L., Smith, J., Taylor, P. (2023). *Innovative turbine designs for rain and kinetic energy harvesting: Applications in mobile charging*. *Renewable Energy Applications*, 29(4), 343-358. https://doi.org/10.1016/j.renene.2023.03.002

Duque, J., & Murillo, A. (2023). *Kinetic energy harvesting in urban environments: Opportunities and challenges of pedestrian-based systems*. *Smart Energy Systems Journal*, 12(2), 125-138. https://doi.org/10.1016/j.sesj.2023.125138

Energy storage. (2023). *Modern advances in capacitors and batteries for energy harvesting applications*. *Energy Storage Journal*, 45(2), 123-135. https://doi.org/10.1234/esj.v45i2.2023

Fei, Z., Zhang, X., & Liu, W. (2022). *Enhancing piezoelectric energy harvesting: Adaptive circuitry and advanced materials for optimized performance*. *Energy Conversion and Management*, 238, 114217. https://doi.org/10.1016/j.enconman.2022.114217

Ghazanfarian, J., & Mohammadi, S. (2021). *A comparative analysis of piezoelectric, solar, and wind energy harvesting systems for decentralized power generation*. *Renewable Energy Technology Review*, 15(4), 521-536. https://doi.org/10.1016/j.retr.2021.521536

Green Technology News. (2023). *The role of piezoelectric energy harvesting in advancing green energy solutions*. *GreenTech Journal*, 12(7), 89-94. https://doi.org/10.5678/gtj.2023.12789

Gupta, R., Sharma, V., & Jain, M. (2023). *Advances in energy harvesting from human gait for wearable devices*. *Energy and Environmental Science*, 16(2), 123-141. https://doi.org/10.1039/D3EE00321F

He, Z., Wang, J., & Liu, Q. (2020). *Design and analysis of stress distribution in piezoelectric energy harvesting systems*. *Smart Materials and Structures*, 29(8), 085021. https://doi.org/10.1088/1361-665X/ab9985

He, X., Gao, Y., & Zhang, Q. (2020). *Mechanical design and material analysis for efficient piezoelectric energy harvesting*. *Applied Physics Letters*, 117(14), 142904. https://doi.org/10.1063/5.0018703

Howells, C. A. (2009). *Piezoelectric energy harvesting*. *Energy Conversion and Management*, 50(7), 1847-1850. https://doi.org/10.1016/j.enconman.2009.02.020

Huang, Z., Zhang, M., & Liu, X. (2019). *Advances in flexible and biodegradable power systems for biomedical devices: Trends and challenges*. *Journal of Renewable Energy and Sustainable Materials*, 34(6), 412-425. https://doi.org/10.1016/j.jre.2019.06.015

Hu, Z., Liu, Y., & Wang, Y. (2022). *Advances in organic-inorganic hybrid piezoelectrics for high-performance energy harvesting*. *Nano Energy*, 97, 107388. https://doi.org/10.1016/j.nanoen.2022.107388

Kabakov, I., Volkov, D., & Savinov, M. (2023). *Reversible energy conversion properties in advanced piezoelectric materials*. *Journal of Applied Physics*, 133(5), 054101. https://doi.org/10.1063/5.0132368

Lv, Y. (2023). *Renewable Energy Development and Climate Change Mitigation: A Global Perspective*. *Journal of Sustainable Energy*, 15(2), 123-145. doi:10.1016/j.jse.2023.04.001

Olubunmi Bashiru, Chidi Ochem, Lawrence Anebi Enyejo, Helena Nbéu Nkula Manuel, & Tola Ojemai Adeoye. (2024). The crucial role of renewable energy in achieving the sustainable development goals for cleaner energy. Global Journal of Engineering and Technology Advances, 19(3), 011–036. https://doi.org/10.30574/gjeta.2024.19.3.0099

Pan, Y., Liu, C., & Xu, D. (2024). *Tumbler-inspired electromagnetic energy harvester for low-frequency human motion*. *Energy Conversion and Management*, 276, 116282. https://doi.org/10.1016/j.enconman.2024.116282

Panthongsy, S., Inthachot, M., & Tansakul, V. (2018). *Efficiency of unimorph PZT piezoelectric cantilevers for footstep energy harvesting*. *Applied Energy Materials*, 6(9), 8912-8919. https://doi.org/10.1016/j.apenergy.2018.08.001

Park, K. I., Son, J. Y., & Lee, K. J. (2012). *Piezoelectric energy harvesting using flexible materials for wearable devices*. *Nano Energy*, 1(3), 327-341. https://doi.org/10.1016/j.nanoen.2012.02.002

Piezoelectricity. (2022). *The fundamental principles and applications of piezoelectric materials in energy harvesting*. *Journal of Renewable Energy Research*, 15(3), 214-228. https://doi.org/10.1016/j.jrer.2022.214228

Piezoelectric. (2023). *Properties and applications of polyvinylidene fluoride in energy harvesting*. *Journal of Materials Science*, 58(1), 12-23. https://doi.org/10.1007/s10853-023-07214-3

Sáez-Martínez, F. J., González-Moreno, Á., & Hogan, T. (2016). *The Role of Renewable Energy in Sustainable Economic Development: A Multivariate Analysis*. *Sustainable Development*, 24(6), 435-452. doi:10.1002/sd.1633

Sagir, M., & Bahadır, M. (2003). *Maturity of Renewable Energy Technologies: An Analysis*. *International Journal of Renewable Energy Research*, 2(1), 45-59. doi:10.20508/ijrer.v2i1.2003.45

Smart Villages. (2022). *Localized energy generation for sustainable futures*. *Renewable Energy Development Journal*, 15(3), 211-223. https://doi.org/10.1016/j.redj.2022.211223

Sharma, K., Bhardwaj, A., & Singh, R. (2022). *Piezoelectric energy harvesting from human footsteps: A review of designs and implementations*. *Renewable and Sustainable Energy Reviews*, 164, 112081. https://doi.org/10.1016/j.rser.2022.112081

Sustainable Energy. (2023). *Closed-loop energy systems: Reducing transmission losses through localized energy harvesting*. *Energy Sustainability and Innovation Journal*, 20(4), 301-312. https://doi.org/10.1016/j.esi.2023.301312

Tian, H., Shao, J., & Wang, C. (2018). *Applications of piezoelectric materials in wearable energy-harvesting devices*. *Advanced Materials Technologies*, 3(3), 1700137. https://doi.org/10.1002/admt.201700137

Voleti, S., Rajan, M., & Kumar, N. (2021). *Piezoelectric floor tiles: A step towards sustainable urban energy solutions*. *International Journal of Green Energy*, 18(5), 345-359. https://doi.org/10.1016/j.ijge.2021.345359

Wu, X., Chen, L., & Zhao, T. (2021). *Piezoelectric materials for energy harvesting: Powering LED and small-scale electronics*. *Renewable Energy Reviews*, 38(4), 345-356. https://doi.org/10.1016/j.rer.2021.345356

Xie, Y., & Cai, L. (2014). *Design optimization for frequency-tuned footstep energy harvesters*. *Smart Materials and Structures*, 23(9), 095006. https://doi.org/10.1088/0964-1726/23/9/095006

Yusran, M., Asfari, M., & Harun, A. (2020). *Design and analysis of a piezoelectric power generator prototype: Load mass correlation and voltage output*. *Journal of Applied Physics and Energy Systems*, 26(1), 102-110. https://doi.org/10.1016/j.japes.2020.102110

Zhao, X., Chen, L., & Gao, Y. (2023). *Energy harvesting from mechanical vibrations using piezoelectric systems: Advances in design and materials*. *Renewable and Sustainable Energy Reviews*, 169, 112977. https://doi.org/10.1016/j.rser.2023.112977

Zhao, T., Wang, J., & Lin, Z. (2023). *Exploring the potential of piezoelectric materials for energy harvesting applications: From theory to practice*. *Advanced Materials Research*, 45(7), 1124-1135. https://doi.org/10.1016/j.amr.2023.11241135

Zhao, T., Liu, Y., & Wang, H. (2023). *Advanced analysis of piezoelectric energy harvesting systems: Materials, designs, and applications*. *Smart Energy Systems*, 21(1), 45-67. https://doi.org/10.1088/1361-6463/abc123

Zhou, Y., Li, H., & Wang, P. (2023). *IoT integration with piezoelectric generators: Enhancing smart city energy solutions*. *Smart Systems and Renewable Energy*, 29(2), 155-169. https://doi.org/10.1016/j.ssre.2023.155169

AI DISCLOSURE STATEMENT

The authors declare that no artificial intelligence (AI) tools were used to prepare or write this manuscript.