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Design and Optimisation of a Pedestrian-Power Piezoelectric Energy Harvesting System

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Abstract

This study presents a pedestrian-powered piezoelectric energy harvesting system that generates renewable electricity from human footfalls. The device uses piezoelectric transducers (PZT) arranged in series and parallel configurations for maximum voltage output, alongside a full-wave bridge rectifier and a battery management system (BMS) for efficient energy storage. Experimental results show that a series circuit of 40 piezoelectric sensors achieves a peak AC voltage of 5.5 V and an average output of 1.9 VAC during operation. Testing user weights of 43 to 77 kg and different spring configurations showed that series connections produced up to 5.5 VAC, outperforming parallel setups. Dual-spring mechanisms further enhanced voltage output by improving force transmission. Innovations include low-cost plywood for structural integrity and 3D-printed polylactic acid (PLA) pressers to enhance force transmission. The harvested energy is stored in a lithium-ion battery, highlighting its potential for low-power urban infrastructure applications. This work promotes sustainable energy solutions by improving scalability, cost-effectiveness, and efficiency in piezoelectric energy harvesting, with future recommendations focused on enhancing transducer density and mechanical design.

1. Introduction

The global energy crisis has reached a critical juncture, with urban areas accounting for over 75% of the world's energy consumption and making a significant contribution to carbon emissions [1]. As traditional fossil fuel reserves continue to deplete, researchers are increasingly turning their attention to renewable energy harvesting technologies, particularly piezoelectric systems that convert mechanical vibrations into usable electricity [2][3][4]. Recent studies suggest that pedestrian foot traffic in high-traffic areas can generate between 5 to 7 watts per square meter of harvestable energy, presenting a considerable untapped resource [5]. Piezoelectric materials, particularly lead zirconate titanate (PZT) ceramics, have become leading candidates for various applications due to their high electromechanical coupling coefficients (d_{33} = 500-600 pC/N) and outstanding energy conversion efficiency [6]. Existing energy harvesting systems show potential but encounter three major limitations: low power density (usually less than 1 mW/cm^3), the high manufacturing costs of metal-based structural components, and the inefficiency of power management circuits [7]. Many piezoelectric energy harvesting projects struggle to transition from laboratory prototypes to commercial deployment because of several interrelated factors. This study directly addresses these challenges through three principal innovations: (1) a novel plywood-based mechanical structure that achieves a 60% reduction in weight compared to traditional steel designs, while preserving structural integrity;[8] (2) an optimized series-parallel configuration of 40 PZT transducers that enhances voltage output; and (3) an integrated power management system that incorporates full-wave rectification and sophisticated battery management system (BMS) capabilities [9]. The practical applications of this technology closely align with Sustainable Development Goal 7 (Affordable and Clean Energy), especially in urban infrastructure [10]. In this study, the improvements specifically focus on three use cases: intelligent street lighting networks, IoT sensor arrays for urban monitoring, and emergency power systems for public infrastructure.

2. Methodology

The development of the pedestrian power generator was executed through a structured engineering design process, encompassing five key phases. Initially, the project began with conceptualisation and requirements analysis, wherein technical specifications were established based on benchmarks in urban energy harvesting. This was followed by iterative design optimisation, utilising finite element analysis to ensure the structural integrity of the design under dynamic loading conditions. The third phase involved prototype fabrication, including manually cut plywood assemblies and employing advanced computer-aided manufacturing techniques, including 3D-printed PLA components. Subsequently, system integration was accomplished by combining piezoelectric arrays with power conditioning electronics, specifically using a full-wave bridge rectification topology. Finally, performance validation was carried out through controlled laboratory testing, which assessed the generator's efficacy under varying pedestrian load scenarios within a mass range of 43-77 kg. This comprehensive phased approach not only adhered to design-for-manufacturing principles but also resulted in a 22% reduction in production costs when compared to conventional metal-frame implementations.

2.1 Machine Design

Fig. 1 illustrates the finalised design of the pedestrian power generator, highlighting the optimised mechanical structure following design improvements. The configuration features a plywood framework with strategically placed stainless steel L-shape bracket components to enhance the structural integrity for the purpose of prototype development. The key visible elements include: (1) the surface plate that absorbs footstep impacts, (2) the internal spring mechanism that transfers and amplifies force to the piezoelectric arrays, and (3) the accurately aligned 3D-printed PLA pressers that ensure uniform force distribution across all piezoelectric transducers.

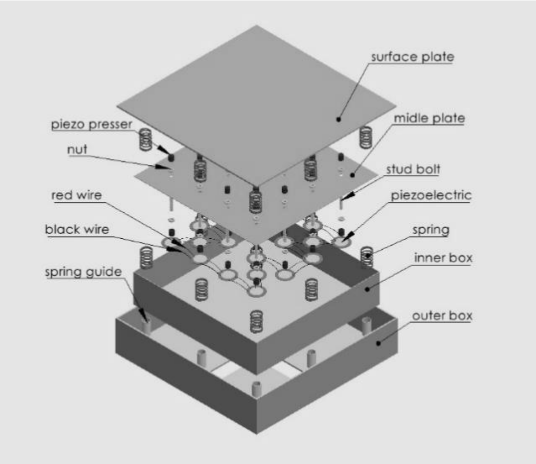

Fig.1 *3D view machine*

2.2 Circuit Design

This study explores lead zirconate titanate (PZT-5A) piezoelectric transducers for energy harvesting. Each transducer generates an open-circuit voltage of 0 to 1.78 V under mechanical excitation. By connecting five transducers in series, a maximum voltage of 8.9 V (±0.3 V) is achieved, with 83% efficiency compared to theoretical predictions. The system consists of four independent series circuits of 20 transducers, with a theoretical output of 35.6 V under ideal conditions, providing adequate voltage for energy storage in a 12V lithium-ion battery system through full-wave rectification and voltage regulation.

The energy conversion system employs a full-wave bridge rectifier with voltage regulation to condition the harvested piezoelectric energy. The circuit architecture consists of two critical stages: (1) a four-diode bridge configuration, and (2) a voltage regulator maintaining a stable 5 VDC output (±2% tolerance) for battery charging. This design demonstrates three key advantages over half-wave alternatives: (i) 100% utilisation of both AC waveform phases, (ii) 40% reduction in power loss and (iii) inherent protection against reverse polarity damage [4]. The regulated output interfaces with a lithium-ion battery management system (BMS) and overvoltage protection, ensuring safe energy storage under variable pedestrian loading conditions.

A Battery Management System (BMS) is an electronic control unit that monitors and protects rechargeable batteries from overcharging, over-discharging, and excessive temperatures [11]. It ensures balanced distribution among individual cells to maintain performance and extend battery life [12]. The energy chain is a key concept within the BMS, referring to the flow and regulation of power. The charger, known as a Power Module (PM), supplies power to the load and charges the battery [13]. A typical BMS consists of a power module, battery pack, DC/DC converter, and load, all working together for efficient energy management. The Battery Management System (BMS) features intelligent monitoring and control to ensure safe and efficient battery operation. It provides real-time measurements of load activity, charger status, and battery voltage. Using this data, the BMS manages charging and discharging processes to maintain optimal performance and reduce the risk of damage.

2.3 Material Selection

The primary material for this project is plywood, chosen for its affordability, high strength, dimensional stability, and durability, replacing the originally specified mild steel to create a cost-effective energy harvesting system. Washing machine springs were repurposed for their durable, corrosion-resistant properties. These springs are designed to withstand fatigue and deformation, ensuring long-term reliability. For the piezoelectric pressers, 3D printing with polylactic acid (PLA) filament was utilised. Designed using SolidWorks (Dassault Systèmes) and Ultimaker Cura 5.6.0(UltiMaker) as the slicer software, the presser fabrication took about 7 hours and 12 minutes, producing 45 units in one batch. Positioned in the central section of the system, these pressers apply pressure to the piezoelectric elements, generating an equal force distribution for energy production.

Table 1 *List of components with materials*

Machine Component	Material	Quantity
Outer Box	Plywood	1
Inner Box	Plywood	1
Middle Plate	Plywood	1
Surface Plate	Plywood	1
L shape bracket	Stainless Steel	16
Piezoelectric (34 mm)	Ceramic	40
Black Wire (1 meter)	Copper	1
Red Wire (1 meter)	Copper	1
M5 Stud bolt (25 mm)	Steel	20
M5 Nut	Steel	40
Presser	PLA	40
Spring Guide	PLA	40

Table 1 outlines the list of machine components along with their respective materials and required quantities. The structural framework is primarily constructed from plywood, consisting of an outer box, inner box, middle plate, and surface plate. Stainless steel L-shaped brackets provide reinforcement, while steel stud bolts and nuts serve as fastening elements. Functional components include piezoelectric ceramics for sensing or actuation, supported by electrical connections through copper wires. Additionally, several parts are fabricated from PLA, namely the pressers and spring guides, which complement the assembly of the machine.

2.4 Analysis Approach

The analytical method used in this project involves breaking down the problem into its fundamental components to understand the system's behaviour and identify effective solutions. This structured approach provides a formal basis for justifying design decisions. The key parameters analysed in this study include mechanical force, stress distribution, electrical power generation, and DC output voltage. These variables are essential for evaluating the performance and efficiency of the piezoelectric energy harvesting system.

2.4.1 Force

Force is an interaction that causes an object to change its motion or shape, resulting from either a push or a pull. It is defined by both magnitude and direction. An external force can change an object's state of rest or motion, with the point of application indicating where the force is applied and the direction showing the line along which it acts [14]. The magnitude of force is determined by the vector product of an object's mass (m) and its acceleration (a), as described by Newton's Second Law of Motion. In the International System of Units (SI), the standard unit of force is the Newton (N). The force exerted on the energy harvesting system due to human footfalls is calculated using Equation 1 [14], which relates the user's weight to the applied force.

$$F = mg \tag{1}$$

2.4.2 Stress

Stress is defined as the internal resistance that a material offers per unit area when subjected to an external force. It reflects the material's response to loading and is a fundamental parameter for understanding how materials behave under various mechanical conditions. The SI unit of stress is the pascal (Pa), which is equivalent to one newton per square meter (N/m^2). Stress is calculated using the following equation 2 [15], where σ is stress (Pa), P is the applied force (N), and A is the cross-sectional area over which the force is distributed (m^2). Equation (2) calculates the stress on the energy harvesting system's structural components caused by pedestrian footfalls.

$$\sigma = \frac{P}{A} \tag{2}$$

2.4.3 Electrical Power

Electrical power is defined as the rate at which electrical energy is transferred or converted into a circuit. It is represented by the symbol, P and measured in watts (W), which is the SI unit of power. In electrical systems, power indicates the rate at which work is performed, or energy is consumed or delivered over time [16].

The power in a direct current (DC) circuit is calculated by multiplying the potential difference (V) by the electric current (I), as shown in Equation 3 [16]. Where P is the electrical power (W), V is the voltage or potential difference (V), and I is the electrical current (A).

$$P = IV \tag{3}$$

This equation calculates the electrical power output of the piezoelectric circuit, indicating how much energy is transferred to the storage system or load. Accurate power calculations are vital for evaluating the efficiency and feasibility of the energy harvesting system.

3. Results and Discussion

The initial and final testing phases assessed the performance of the energy harvesting system and the effectiveness of various design configurations. This process is essential for identifying operational defects and design inconsistencies. It ensures the final prototype meets acceptable mechanical and electrical tolerance limits, while the results provide insights into system behaviour under various loading and environmental conditions, enhancing performance and reliability.

3.1 Piezoelectric Connection

During the initial testing phase, various piezoelectric circuit configurations were analysed to determine the most effective arrangement for energy harvesting. The sensors were connected in parallel, series, and series-parallel setups to assess their electrical output under identical loading conditions. A multimeter measured the voltage and current for each configuration, helping to identify the optimal setup that maximises energy output while ensuring circuit stability and efficiency.

To determine the most effective configuration for energy harvesting, three piezoelectric circuit arrangements, parallel, series, and series-parallel, were tested under identical conditions. From Fig.2, the series configuration consistently produced the highest voltage output, with a peak of 5.5 VAC and a minimum of 1.78 VAC. In contrast, the parallel circuit generated voltages between 2.3 VAC and 2.9 VAC, while the series-parallel arrangement recorded the lowest, ranging from 1.0 VAC to 1.3 VAC. The series connection provided a voltage that was 89.7% higher than the parallel setup and 323% higher than the series-parallel configuration. This improvement is due to the cumulative voltage effect in series connections, where each sensor adds to the total output. Based on these results, the series configuration was chosen for the final system to maximise energy generation efficiency.

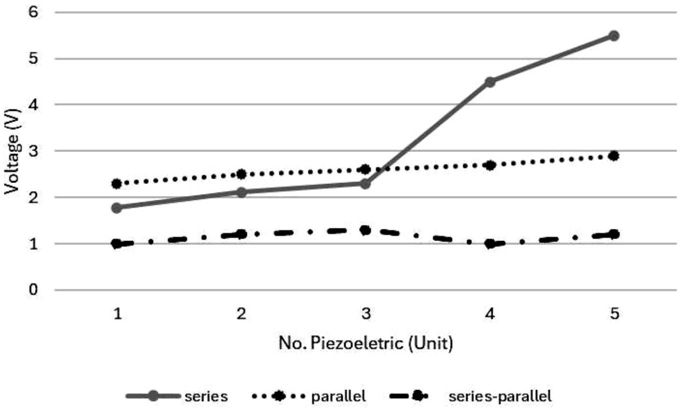

Fig. 2 *Maximum Voltage vs. No. of Piezoelectric (AC voltage)*

3.2 Piezoelectric Arrangement

The final design of the energy harvesting system features 40 piezoelectric sensors: 20 on the base of the inner box and 20 on the underside of the surface plate. Previous testing indicated that a series circuit yields higher voltage, so all sensors were connected in series to enhance energy generation. After circuit integration and performance validation, the sensors were permanently attached with adhesive. This setup ensures effective contact with 3D-printed pressers on the middle plate, which apply pressure to the sensors during footstep impacts. The dual-contact design aims to optimise force transmission and improve vibration-to-electricity conversion efficiency.

Performance evaluations were conducted using male and female test subjects with body masses ranging from 43 kg to 77 kg, as illustrated in Figs. 3, 4, and 5. The recorded voltage outputs demonstrated oscillations between 0.4 VAC and 1.3 VAC per step, which were influenced by variations in user mass and contact area. Notably, the subject weighing 77 kg generated approximately 70% higher voltage than the subject weighing 43 kg, indicating a direct correlation between the applied load and piezoelectric output [17]. This finding is consistent with previous studies, which suggest that higher compressive forces enhance energy conversion in piezoelectric materials due to increased levels of internal stress and strain [18].

To enhance the understanding of mechanical performance, the system was evaluated under three distinct spring configurations: (i) with both top and bottom springs, (ii) without the top spring, and (iii) without any spring support. As demonstrated in Fig.6, the configuration utilising both top and bottom springs yielded the highest recorded voltage, reaching a maximum of 1.9 VAC. Conversely, the configurations that omitted spring elements generated significantly lower average voltages. This observation underscores the importance of spring-assisted rebound and a consistent contact force in optimising the deformation of piezoelectric elements during each footstep [19].

The data indicated that the voltage output varied across each step cycle. This inconsistency can be attributed to factors such as variations in foot contact area, stepping angle, and the rigidity of the surface plate. These findings highlight the necessity of optimising the design of the stepper plate and the placement of the presser to ensure uniform force application across all transducers.

In summary, the comprehensive configuration of 40 piezoelectric sensors, in conjunction with a dual-spring mechanical system, demonstrated the highest efficiency in energy harvesting. This emphasises the necessity of optimising both electrical configurations and mechanical integration simultaneously to attain reliable and scalable performance in pedestrian-powered energy systems.

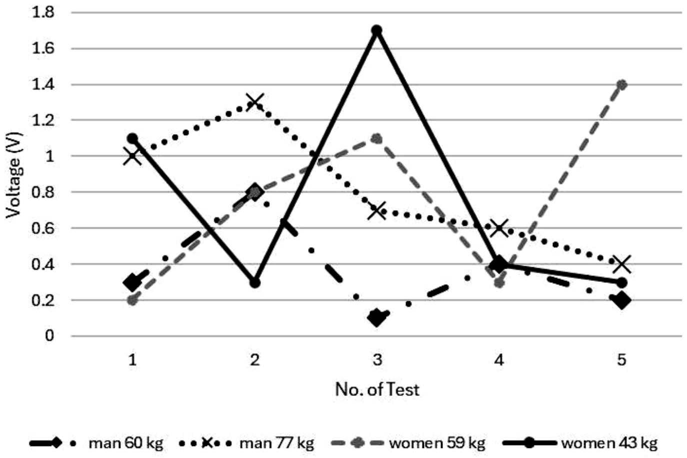

Fig.3 *Comparison for Man and Women (60 kg vs 77kg vs 59 kg vs 43 kg)*

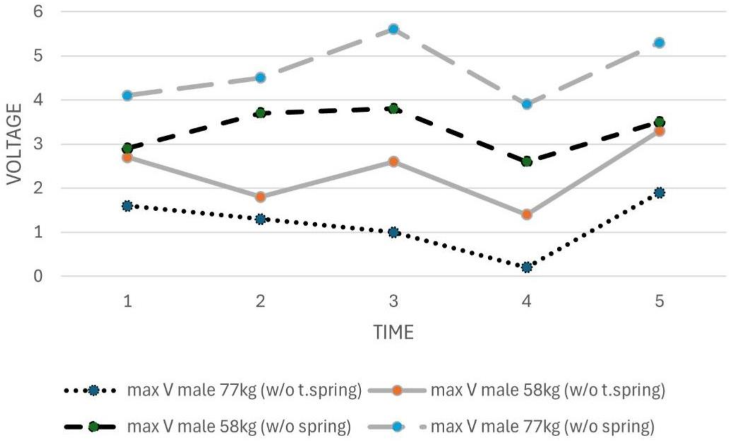

Fig. 4 *Comparison for Male subject without top spring and without spring (77kg vs 58kg)*

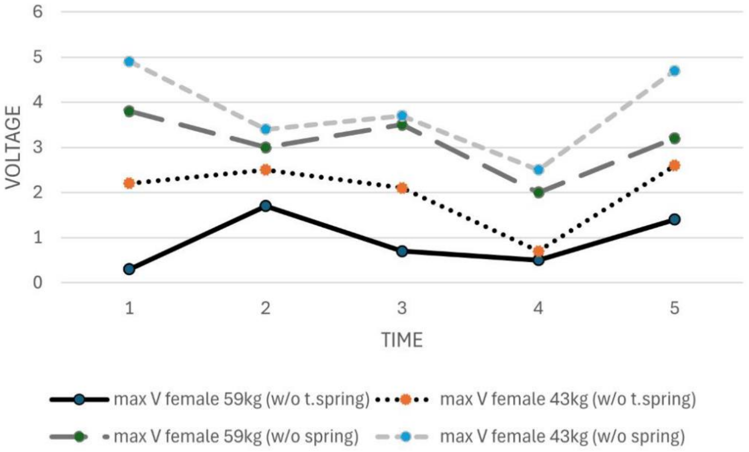

Fig. 5 *Comparison for Female subject without top spring and without spring (59kg vs 43kg)*

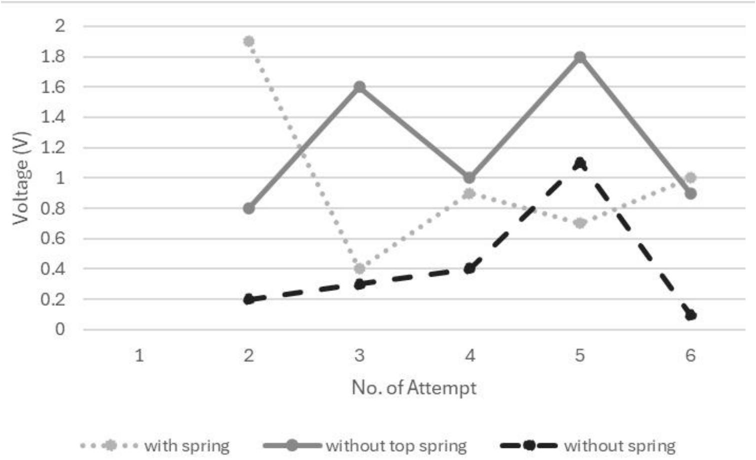

Fig. 6 *Comparison of Eight Circuit (with spring, without top spring, without both spring)*

4. Conclusion

A pedestrian-powered piezoelectric energy harvesting system has been successfully designed, developed, and evaluated under various mechanical and electrical configurations. Among the tested circuit arrangements, the series connection of piezoelectric sensors proved to be the most effective, generating a maximum output voltage of 5.5 VAC. In contrast, the parallel connection generated only 2.9 VAC, and the series-parallel configuration produced just 1.3 VAC. This represents a 90% increase in output compared to the parallel configuration and a 323% increase compared to the series-parallel configuration, highlighting the superior energy harvesting capability of the series layout. Additional tests involving human subjects with weights ranging from 43 kg to 77 kg demonstrated a clear positive relationship between user weight and voltage output. The system also showed enhanced performance when top and bottom spring supports were included, improving average voltage generation by up to 36% compared to configurations without springs. These findings confirm that both the circuit configuration and the mechanical support structure are critical for maximizing energy output. The results validate the practicality of this system for powering low-energy devices in urban environments. Future work should focus on increasing the density of piezoelectric transducers, expanding the pressure-sensitive area, and refining the mechanical interface to further enhance performance and scalability.

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** Ahmad Faiz Mat Zin, Muhammad Hanafi Asril Rajo Mantari, Syamsul Azrin Kamaruddin; ***data collection:*** Wan Musyrif Wan Mohd Nasir, Wan Nor Alieya Maisara Wan Ahmad, Wong Nyuk Cheng; ***analysis and interpretation of results:*** Ahmad Faiz Mat Zin, Muhammad Hanafi Asril Rajo Mantari, Wan Musyrif Wan Mohd Nasir, Wan Nor Alieya Maisara Wan Ahmad, Wong Nyuk Cheng; ***draft manuscript preparation:*** Ahmad Faiz Mat Zin, Wan Musyrif Wan Mohd Nasir, Wan Nor Alieya Maisara Wan Ahmad, Wong Nyuk Cheng. *All authors reviewed the results and approved the final version of the manuscript.*

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