



Wearable Energy Harvester: Application of Piezoelectric Sensors in Shoes as a Portable Power Source

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ABSTRACT

Purpose of the study: This study aims to analyze the effect of variations in pressure loading on piezoelectric sensors mounted on shoes on the amount of electrical power generated and to compare the performance of series and parallel circuit configurations in real-time energy harvesting applications.

Methodology: This study used an experimental method with a ceramic piezoelectric sensor (2 cm diameter), a digital multimeter, a shoe insole, a 100 μ F 25 V capacitor, a 1N4002 diode, connecting cables, and a soldering tool. Data were collected with variations in body weight (52.65 kg–72.65 kg) and gait speed (normal walking, fast walking, running) for 2 km for series and parallel configurations.

Main Findings: The results showed that the greater the pressure due to body weight, the higher the electrical power generated. The series circuit produced a maximum power of 3.39 μ W, while the parallel circuit reached 51.2 μ W at varying weights. At varying speeds, running produced the highest power, with a maximum of 42.56 mW in the parallel configuration. This demonstrates that circuit configuration and pressure significantly influence power output.

Novelty/Originality of this study: This research presents a wearable prototype that integrates piezoelectric sensors, shoe design, and a power storage system for real-time energy harvesting. Unlike previous research limited to simulations, this study demonstrates a functional prototype capable of charging low-power devices, thus supporting sustainable energy technologies and developing the application of piezoelectric principles to portable energy sources.

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1. INTRODUCTION

The need for electrical energy is increasing along with technological developments and the high human dependence on portable electronic devices [1]-[3]. Mobile phones, smartwatches, and IoT devices have become an integral part of daily activities [4], [5]. However, the availability of stable electrical energy remains a challenge, especially in remote areas or times of high mobility [6], [7]. This has led to various innovations in the development of alternative energy sources. One interesting approach is harnessing mechanical energy from human activity.

The mechanical energy generated from footsteps is a renewable energy potential that has not been widely utilized [8]-[10]. Daily walking activities produce significant pressure forces that can be converted into electrical energy [11]-[13]. Energy harvesting technology offers a solution for converting this energy into usable

electricity. With this approach, humans not only move but also generate energy [14]-[16]. The use of this energy is very much in line with the trend of developing environmentally friendly energy.

One of the technologies that can be used to convert mechanical energy into electrical energy is piezoelectricity [17]-[19]. Piezoelectric sensors work on the principle that certain materials are able to produce an electrical voltage when subjected to mechanical pressure [20]-[22]. This material has been extensively researched in a variety of applications, from pressure sensors to small-scale energy generators. The advantages of piezoelectric sensors are their small size, fast response, and ability to be mounted on a variety of media [23]-[25]. With these characteristics, piezoelectricity has great potential to be used in shoes as a micro power generator.

Several previous studies have shown the successful use of piezoelectrics for small-scale power generation applications [26], [27]. However, most research remains limited to laboratory simulations or static load testing. Real-world implementation in the form of wearable devices, such as shoes, remains very limited. Yet, shoes are an ideal medium because each footstep generates repetitive and measurable pressure. This opens up opportunities for developing practical and portable energy harvesting systems. Using piezoelectric shoes as low-power power generators offers significant benefits for users of portable electronic devices. The energy generated can be stored in small batteries to charge devices such as digital watches, health sensors, or wearable devices [28]-[30]. This way, users won't always be dependent on conventional electricity sources. This technology also supports the concept of green energy by utilizing previously wasted energy. This implementation is expected to increase community energy independence. In addition to its practical benefits, this research also makes an academic contribution to the field of applied physics. The principle of piezoelectricity, as part of materials physics, is directly applied in everyday life [31], [32]. This study also incorporates electronics aspects in designing power storage systems. Thus, this research is multidisciplinary, connecting physics, materials engineering, and energy technology. This makes the research not only practically useful but also scientifically relevant.

The research conducted by Iqbal et al., focuses on the development of power harvesting footwear based on a piezo-electromagnetic hybrid generator, emphasizing the technical aspects of the design and the potential energy that can be generated to support portable microelectronic devices [33]. Meanwhile, the research by Zhao et al., presents a broader literature review on the principles, methods, and applications of piezoelectric footwear energy harvesters, so its contribution is more conceptual and provides a global research map without detailed implementation exploration [34]. Both studies are still limited to technical aspects and theoretical reviews, without deeply integrating the applicability potential and sustainability of piezoelectric energy use in shoes in the context of daily energy needs. Therefore, the current research is present to fill this gap by testing the practical application of piezoelectric sensors in footwear, assessing the feasibility of utilizing them as portable power sources, and linking this technology to the trend of sustainable wearable electronics.

The novelty of this research lies in the direct application of piezoelectric sensors in the form of shoes that are capable of harvesting energy in real-time through series and parallel circuit configurations. Unlike previous studies that were still limited to simulations or literature reviews, this study presents a functional prototype that can be used to charge low-power devices. The urgency of this research is increasingly high considering the increasing need for portable energy along with the development of smart devices and the trend of high human mobility. Energy generated from footsteps not only provides a practical solution for users but also supports the development of environmentally friendly renewable energy. Thus, the main objective of this study is to analyze the effect of pressure variations on piezoelectric sensors on the electrical power generated and compare the performance of series and parallel circuit configurations in wearable energy harvesting applications.

2. RESEARCH METHOD

This research falls into the experimental research category, where the variables and measurement methods have been previously determined [35], [36]. The primary goal is to harness the interaction of pressure generated by human footsteps with piezoelectric material to generate electrical energy. Variations used include differences in the shoe user's weight and pressure variations based on walking speed: normal walking, fast walking, and running, over a distance of 2 kilometers. The equipment and materials used in this research consisted of 10 2 cm diameter piezoelectric ceramics, 1 shoe (shoe insole), 1 100 μ F 25 V capacitor, 14 1N4002 diodes, connecting cables, glue, and solder.

The creation and design of a prototype utilizing piezoelectric sensors as an electric generator was carried out using two methods: series and parallel arrangement. The prototype was designed by connecting several piezoelectric sensors to form a generator capable of producing voltage and electric current.

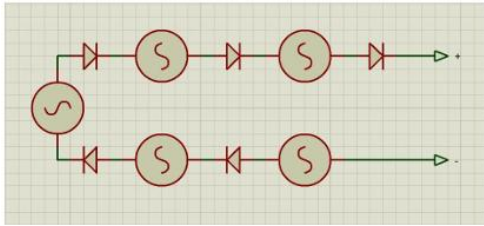


Figure 1. Piezoelectric Series Circuit Schematic

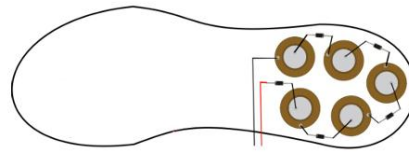


Figure 2. Piezoelectric Series Circuit Inside a Shoe

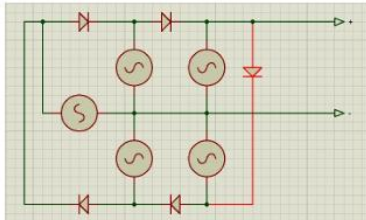


Figure 3. Piezoelectric Parallel Circuit Schematic

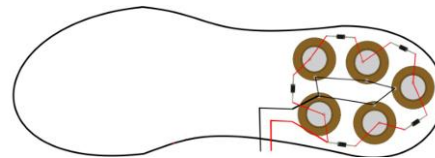


Figure 4. Piezoelectric Parallel Circuit Inside a Shoe

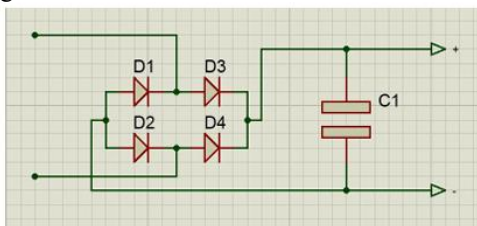


Figure 5. Rectifier Circuit Schematic

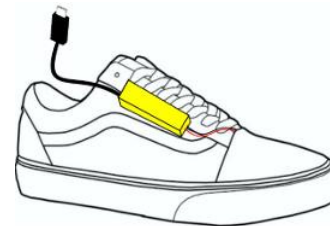


Figure 6. Piezoelectric Battery Charging Shoe

The prototype series circuit began with five piezoelectric sensors and five diodes connected in series. The diodes and capacitors were then arranged to form a rectifier circuit. The rectifier circuit was then connected to the piezoelectric array in parallel to stabilize the current and voltage. In the final stage, two wires were left as output paths, which would be used to measure the electrical output.

Meanwhile, the prototype parallel circuit was constructed by connecting five piezoelectric sensors and five diodes in parallel. Next, the diodes and capacitors were reassembled to form a rectifier circuit to convert alternating current to direct current. The rectifier circuit was connected to the parallel piezoelectric array to produce voltage and current according to its characteristics. As with the series circuit, two output wires were also prepared to measure the system's output.

The data taken from this study is the difference in battery percentage before and after being given pressure from different treatment variations which will be recorded in the following Table (1-2).

Table 1. Data on Power Measurement Results with Body Weight Variations

No.	Body Weight (Kg)	Voltage (V)	Current (A)	Power (W)
1.	52.65			
2.	62,65			
3.	72,65			

Table 2. Power Measurement Results Data with Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking			
2.	Brisk Walking			
3.	Running			

3. RESULTS AND DISCUSSION

Data collection was conducted using a digital multimeter to measure the voltage and current generated by the prototype. Testing was conducted with varying user weights ranging from 52.65 kg to 72.65 kg to obtain output voltage and current data. Furthermore, testing was conducted with varying gait speeds: normal walking, fast walking, and running for 2 km. The data collection process involved two types of testing: a series circuit and a parallel circuit, with each variation applied to both configurations.

Testing with varying user weights was conducted without using a rectifier circuit, in both series and parallel configurations, with the goal of achieving maximum piezoelectric output. Meanwhile, testing based on

varying gait speeds was conducted using a rectifier circuit in both circuits to ensure the prototype produced a more stable output. In the rectifier circuit, a capacitor functions as a temporary storage device for the electrical energy generated by the prototype.

3.1 Power Measurement Results Data with Body Weight Variation

Testing with varying weights of shoe users was carried out by applying pressure in the form of loads of 52.65 kg; 62.65 kg; and 72.65 kg to the prototype circuit. To obtain the voltage measurement results, a multimeter was connected in parallel with the prototype, while to measure the current, a multimeter was connected in series with the prototype and given a load in the form of an LED. The results obtained from testing the prototype with a series circuit are as follows Table 3.

Table 3. Series Circuit Testing With Weight Variations

No.	Body Weight (Kg)	Voltage (V)	Current (A)	Power (W)
1.	52.65	1.8	1.1	2.01
2.	62,65	1.92	1.44	2.76
3.	72,65	1.95	1.74	3.39

Table 3 shows the output values produced by the prototype with a series circuit. The data above is a series circuit test with 3 different body weight variations. The first test on a prototype with a body weight of 52.65 kg obtained a voltage of 1.8 V and a current of 1.1 μ A resulting in a power of 2.01 μ W. The second test using a body weight of 62.65 kg obtained a voltage of 1.92 V and a current of 1.44 μ A resulting in a power of 2.76 μ W. The third test using a body weight of 72.65 kg obtained a voltage of 1.95 V and a current of 1.74 μ A resulting in a power of 3.39 μ W. The results obtained in the prototype test with a parallel circuit are as follows Table 4.

Table 4. Parallel Circuit Testing With Weight Variations

No.	Body Weight (Kg)	Voltage (V)	Current (A)	Power (W)
1.	52.65	4.37	9.3	40.64
2.	62,65	4.8	9.56	45.88
3.	72,65	5.02	10.2	51.2

Table 4 shows the output values produced by the prototype with a parallel circuit. The data above represents parallel circuit testing with three different body weight variations. The first test, using a prototype weighing 52.65 kg, yielded a voltage of 4.37 V and a current of 9.3 μ A, resulting in a power output of 40.64 μ W. The second test, using a body weight of 62.65 kg, yielded a voltage of 4.8 V and a current of 9.56 μ A, resulting in a power output of 45.88 μ W. The second test, using a body weight of 62.65 kg, yielded a voltage of 5.02 V and a current of 10.2 μ A, resulting in a power output of 51.2 μ W.

Based on the graph above, as the body weight increases, the resulting power increases. This illustrates the relationship between the effects of material electrical behavior and Hooke's Law. When a piezoelectric sensor is subjected to pressure, the piezoelectric material stretches, causing a shift in the electrical charge density within the piezoelectric sensor and generating an electric field. The first test, using a series-connected prototype, yielded power outputs of 2.01 μ W, 2.76 μ W, and 3.39 μ W, respectively. The second test, using a parallel-connected prototype, yielded power outputs of 40.64 μ W, 45.88 μ W, and 51.2 μ W, respectively. Based on the data above, the greater the weight exerted on the piezoelectric sensor, the greater the power output. This explains the relationship between the electrical behavior of materials and Hooke's Law. When a piezoelectric sensor is subjected to pressure, the piezoelectric material stretches, causing a shift in the electrical charge density within the piezoelectric sensor and generating an electric field.

So it can be concluded, the greater the pressure applied to the piezoelectric sensor, the greater the output value will be. Furthermore, the prototype with a series circuit produces much less power than the prototype with a parallel circuit. This could be due to the nature of piezoelectricity itself. When pressure is applied, the piezoelectric will produce an electric charge, and when pressure is released, the piezoelectric will absorb the electric charge. In the prototype with a series circuit, the flow of electric charge must pass through each piezoelectric one by one. Under normal conditions, when the piezoelectrics can be pressed simultaneously, the amount of charge released can be maximized. Meanwhile, in this prototype, there are several parts that are not pressed, so the charge released is not optimal.

3.2 Power Measurement Results Data with Speed Variations

Testing at varying speeds was conducted by applying pressure from a 52.65 kg shoe wearer during normal walking, fast walking, and 2 km running on a prototype circuit connected to a rectifier circuit containing a diode and capacitor. This resulted in a more stable voltage and current output and allowed the total output to be

stored in the capacitor. To obtain the voltage measurements, a multimeter was connected in parallel with the capacitor in the rectifier circuit. To measure the current, the multimeter was connected in series with the capacitor in the rectifier circuit and provided with an LED load.

This test was repeated three times, resulting in varying output values and an average value. The results obtained from the first series prototype test are as follows Table 5.

Table 5. First Test of Series Circuit With Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking	4.71	0.57	2.68
2.	Brisk Walking	4.5	0.54	2.43
3.	Running	5.22	0.63	3.28

Table 5 shows the output values produced by the prototype with a series circuit. The data above represents a series circuit test with 3 different speed variations. The first test on the prototype at a normal walking speed obtained a voltage of 4.71 V and a current of 0.57 mA, resulting in a power of 2.68 mW. The second test at a fast walking speed obtained a voltage of 4.5 V and a current of 0.54 mA, resulting in a power of 2.43 mW. The third test at a running speed obtained a voltage of 5.22 V and a current of 0.63 mA, resulting in a power of 3.28 mW. The results obtained in the second series circuit prototype test are as follows Table 6.

Table 6. Testing of the Two Series Circuits with Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking	4.68	0.52	2.43
2.	Brisk Walking	4.45	0.5	2.25
3.	Running	5.17	0.6	3.11

Table 6 shows the output values produced by the prototype with a series circuit. The data above represents a series circuit test with 3 different speed variations. The first test on the prototype at a normal walking speed obtained a voltage of 4.68 V and a current of 0.52 mA, resulting in a power of 2.43 mW. The second test at a fast walking speed obtained a voltage of 4.45 V and a current of 0.5 mA, resulting in a power of 2.25 mW. The third test at a running speed obtained a voltage of 5.17 V and a current of 0.6 mA, resulting in a power of 3.11 mW. The results obtained in the third series circuit prototype test are as follows Table 7.

Table 7. Testing of the Three Series Circuits with Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking	4.66	0.46	2.18
2.	Brisk Walking	4.27	0.46	1.99
3.	Running	4.96	0.5	2.49

Table 7 shows the output values produced by the prototype with a series circuit. The data above represents a series circuit test at three different speed variations. The first test, using a standard walking speed, yielded a voltage of 4.66 V and a current of 0.46 mA, producing 2.18 mW of power. The second test, using a fast walking speed, yielded a voltage of 4.27 V and a current of 0.46 mA, producing 1.99 mW of power. The third test, using a running speed, yielded a voltage of 4.96 V and a current of 0.5 mA, producing 2.49 mW of power. The data from the first and third series circuit tests with varying speeds showed lower output values. This is due to the presence of a rectifier circuit within the circuit, resulting in a smaller and more stable output value. Furthermore, the measurement data showed a modest difference. Although some decreases occurred, they were not significant.

In the first test, the power output was 2.68 mW at a standard walking pace; 2.43 mW at a fast pace; and 2.43 mW at a fast pace. and 3.28 mW when running. The second test obtained a power output of 2.43 mW when walking normally; 2.25 mW when walking fast; and 3.11 mW when running. The third test obtained a power output of 2.18 mW when walking normally; 1.99 mW when walking fast; and 2.49 mW when running. Based on the graph above, the best speed variation in making piezoelectrics produce electricity is by running. So the capacitor is able to store enough electrical energy to increase and stabilize the voltage.

Based on the above tests, it can be concluded that when walking normally, the piezoelectric receives input with a moderate frequency and pressure. When walking fast, the piezoelectric receives input with a higher frequency and lower pressure, this causes a smaller power output value because the body position becomes more inclined forward and the downward pressure used is very minimal to continue to the next movement. When running, the piezoelectric receives input with a higher frequency and pressure, thus producing a greater power output value because it has a higher tread frequency and uses a greater downward pressure. The results obtained in the prototype test with the first parallel circuit are as follows Table 8.

Table 8. First Test of Parallel Circuit With Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking	8.85	3.8	33.63
2.	Brisk Walking	8.12	3.48	28.25
3.	Running	9.85	4.22	42.56

Table 8 shows the output values produced by the prototype with a parallel circuit. The data above represents a parallel circuit test with 3 different speed variations. The first test on the prototype at a normal walking speed obtained a voltage of 8.85 V and a current of 3.8 mA, resulting in a power of 33.63 mW. The second test at a fast walking speed obtained a voltage of 8.12 V and a current of 3.48 mA, resulting in a power of 28.25 mW. The third test at a running speed obtained a voltage of 9.85 V and a current of 4.22 mA, resulting in a power of 41.56 mW. The results obtained in the second prototype test with a parallel circuit are as follows Table 9.

Table 9. Testing of the Two Parallel Circuits with Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking	8.58	3.37	28.99
2.	Brisk Walking	8	3.24	25.98
3.	Running	9.71	4.01	38.99

Table 9 shows the output values produced by the prototype with a parallel circuit. The data above represents a parallel circuit test with 3 different speed variations. The first test on the prototype at a normal walking speed obtained a voltage of 8.58 V and a current of 3.37 mA, resulting in a power of 28.99 mW. The second test at a fast walking speed obtained a voltage of 8 V and a current of 3.24 mA, resulting in a power of 25.98 mW. The third test at a running speed obtained a voltage of 9.71 V and a current of 4.01 mA, resulting in a power of 38.99 mW. The results obtained in the third prototype test with a parallel circuit are as follows Table 10.

Table 10. Testing of the Three Parallel Circuits with Speed Variations

No.	Speed	Voltage (V)	Current (A)	Power (W)
1.	Normal Walking	8.53	3.04	25.94
2.	Brisk Walking	7.94	3.1	24.68
3.	Running	9.68	3.48	33.77

Table 10 shows the output values produced by the prototype with a parallel circuit. The data above represents parallel circuit testing at three different speed variations. The first test, using a normal walking speed, yielded a voltage of 8.53 V and a current of 3.04 mA, producing 25.94 mW of power. The second test, using a fast walking speed, yielded a voltage of 7.94 V and a current of 3.1 mA, producing 24.68 mW of power. The third test, using a running speed, yielded a voltage of 9.68 V and a current of 3.48 mA, producing 33.77 mW of power.

The first test yielded a power output of 33.63 mW at normal walking; 28.25 mW at fast walking; and 41.56 mW at running. The second test yielded a power output of 28.99 mW at normal walking; 25.98 mW at fast walking; and 38.99 mW at running. The third test yielded a power output of 25.94 mW during normal walking; 24.68 mW during brisk walking; and 33.77 mW during running. Based on the graph above, the best speed variation for making the piezoelectric generate electricity is running. This allows the capacitor to store enough electrical energy to increase and stabilize the voltage.

Based on the above tests, it can be concluded that during normal walking, the piezoelectric receives input at a moderate frequency and pressure. When brisk walking, the piezoelectric receives input at a higher frequency and lower pressure. This results in a lower power output because the body is more inclined forward and the downward force used is minimal to allow for the next movement. When running, the piezoelectric receives input at a higher frequency and pressure, resulting in a higher power output due to the higher tread frequency and greater downward force. Data generated from the first three parallel circuit tests with varying speeds showed a higher output value than the series circuit. This is because in a series circuit, the current of each piezoelectric element is absorbed by the other, resulting in a less than optimal output value [37], [38]. This contrasts with a parallel circuit, where the current of each piezoelectric element flows directly to the output measurement point, resulting in a higher output value.

The results of the study showed that pressure variations due to differences in body weight significantly affected the electrical power generated by the piezoelectric sensor. The greater the load applied to the shoe insole, the higher the voltage and current generated, thus increasing the electrical power [39], [40]. This is consistent with the basic principles of the piezoelectric effect and Hooke's law, where greater compressive force

causes greater deformation in the material, resulting in a higher electrical charge density [41], [42]. These findings confirm that user biomechanical factors, such as body weight, are important determinants in optimizing wearable energy harvesting systems.

In addition to pressure variations, walking speed was also shown to influence electrical power output. Tests showed that running generated the highest power output compared to normal or fast walking. This can be explained by the fact that when running, the stride frequency and pressure increase, so the sensor receives mechanical input with higher intensity and repetition [43], [44]. Conversely, when walking fast, the downward pressure is relatively smaller because the force distribution is more directed toward forward motion, resulting in lower electrical power output than when walking normally. These findings demonstrate that not only force magnitude but also the pattern of force distribution determines the effectiveness of piezoelectric energy harvesting.

A comparison of circuit configurations shows that a parallel arrangement generates significantly more power than a series arrangement. This occurs because in a parallel circuit, each piezoelectric sensor has a direct path to the output, allowing for optimal current accumulation [45], [46]. Conversely, in a series circuit, the outputs of each sensor are interdependent, so if any sensor is not stressed, the energy released is not maximized. These findings provide empirical evidence that circuit design plays a critical role in improving the performance of wearable harvester devices, and that a parallel configuration is more suitable for real-world applications involving non-uniform step pressure.

The results of this study align with the study by Iqbal et al., which emphasized the potential of hybrid energy shoes [33], and also extend the study by Zhao et al., by providing evidence of a real-world prototype capable of charging low-power devices [34]. The advantage of this study is that it places the piezoelectric system in the context of an applicable wearable prototype, addressing a gap in previous research that has been limited to conceptual aspects or laboratory simulations. Thus, this research not only strengthens the theory of piezoelectricity as an alternative energy source but also opens up opportunities for implementation in everyday wearable devices that support the transition to sustainable energy. The results of this study have important implications for the development of wearable energy harvesting technology. First, the application of piezoelectricity in shoes opens up significant opportunities to provide a portable energy source that can power low-power electronic devices, such as digital watches, health sensors, or IoT devices. Second, the finding that parallel configurations are superior to series configurations can provide a technical design basis for further research and the development of more efficient commercial products. Third, this study contributes to the concept of green technology by utilizing previously wasted biomechanical energy, thus supporting the sustainable energy agenda and reducing dependence on conventional electricity sources.

Despite its significant contribution, this study has several limitations. First, the tests were conducted only with a limited range of body weights and simple walking/running scenarios, so they do not represent more complex real-world conditions, such as varying terrain, varying footwear, or long-term wear duration. Second, this study used a relatively small number of piezoelectric sensors, thus limiting the power output capacity for devices with higher energy requirements. Third, this study focused on laboratory measurements and limited trials, without exploring aspects of user comfort or material durability in everyday use. Therefore, further research is needed to test the prototype on a larger scale, evaluate ergonomic comfort, and integrate a more efficient energy storage system.

4. CONCLUSION

The conclusion of this study shows that there is a significant influence of pressure loading on the piezoelectric sensor on the amount of electrical power produced, where the greater the pressure from the body weight given to the sensor, the higher the value of the electrical output produced. In addition, the circuit configuration also affects the amount of electrical power; the series circuit configuration produces less power compared to the parallel circuit configuration. This occurs because in a series circuit, the current produced by each piezoelectric is absorbed by the other piezoelectric so that the output is not optimal, whereas in a parallel circuit, the current from each piezoelectric goes directly to the output measurement point so that it produces a larger output value.

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